

MODIFIED SCHEELITE MATERIAL FOR CO-FIRING

INCORPORATION BY REFERENCE TO ANY PRIORITY APPLICATIONS

[0001] This application claims priority to U.S. App. No. 62/686,191, filed June 18, 2018, the entirety of which is incorporated by reference herein.

BACKGROUND

Field

[0002] Embodiments of the disclosure relate to co-fireable dielectric materials that can be formed without the use of adhesives.

Description of the Related Art

[0003] Circulators and isolators are passive electronic devices that are used in high-frequency (e.g., microwave) radio frequency systems to permit a signal to pass in one direction while providing high isolation to reflected energy in the reverse direction. Circulators and isolators commonly include a disc-shaped assembly comprising a disc-shaped ferrite or other ferromagnetic ceramic element, disposed concentrically within an annular dielectric element.

[0004] A conventional process for making the above-referenced composite disc assemblies is illustrated by the flow diagram of **Figure 1**. At step **12**, a cylinder is formed from a dielectric ceramic material. At step **14**, the (unfired or “green”) cylinder is then fired in a kiln (commonly referred to simply as “firing”). Thus, the ceramic material is “fireable”. At step **16**, the outside surface of the cylinder is then machined to ensure its outside diameter (OD) is of a selected dimension. Achieving precise dimensions in the assembly elements is important because the dimensions affect microwave waveguide characteristics. At step **18**, the inside surface of the cylinder is similarly machined to ensure its inside diameter (ID) is of a selected dimension. In addition, at step **20**, a rod is formed from a magnetic ceramic material. At step **22**, the rod is then fired, and at step **24** its surface is machined to a selected OD. The rod OD is slightly less than the cylinder OD so that the rod can be fitted securely within the cylinder, as described below. Achieving a close fit that promotes good adhesion

between the rod and cylinder is a reason that both the outside surface of the rod and the inside surface of the cylinder are machined to precise tolerances.

[0005] At step 26, epoxy adhesive is applied to the one or both of the rod and cylinder. At step 28, the rod is inserted inside the cylinder to form a rod-and-cylinder assembly, and the epoxy is allowed to cure (harden), as indicated by step 30. At step 32, the outside surface of the rod-and-cylinder assembly is again machined to a precise OD. Lastly, at step 34, the rod-and-cylinder assembly is sliced into a number of disc assemblies. Each disc assembly thus comprises a magnetic ceramic disc disposed concentrically within a dielectric ceramic ring. Each disc assembly is typically several millimeters in thickness.

[0006] The time involved in machining the inside surface of the cylinder to promote adhesion, applying epoxy to the parts, carefully handling and assembling the epoxy-laden parts, and curing the epoxy, contributes to inefficiency in the process. It would be desirable to provide a more efficient method for making composite magnetic-dielectric disc assemblies.

SUMMARY

[0007] Disclosed herein are embodiments of a composite material for use as a radiofrequency component comprising a magnetic garnet material rod, and a ring surrounding the magnetic garnet material rod, the ring being formed from a scheelite material having a firing temperature of 950 °C or below.

[0008] In some embodiments, the scheelite material can have the chemical formula $\text{Li}_{0.05}\text{Bi}_{0.95}\text{Mo}_{0.1}\text{V}_{0.9}\text{O}_4$. In some embodiments, the scheelite material can have the chemical formula $\text{Bi}_{1-2x-z}\text{R}_z\text{M}'_x\text{V}_{1-x}\text{M}''_x\text{O}_4$, R being a rare earth element La, Ce, Pr, Sm, Nd, Gd, Dy, Tb, Ho, Er, Tm, Yb, Lu, Y or Sc, M' being Li, Na, or K, and M'' being Mo or W. In some embodiments, the scheelite material can have the chemical formula $(\text{Na,Li})_{0.5x}\text{Bi}_{1-0.5x}(\text{Mo,W})_x\text{V}_{1-x}\text{O}_4$, x being between 0 and 0.5. In some embodiments, the scheelite material can include between 1 and 10 wt. % aluminum oxide. In some embodiments, the scheelite material can include between 2 and 6 wt. % aluminum oxide. In some embodiments, the magnetic garnet material rod can include Bi, Ca, Zr, Y, Fe, and O. In some embodiments, the scheelite material can include BiVO_4 . In some embodiments, the ring can reduce in diameter

around the magnetic garnet material rod during firing so that no adhesive is used to connect the ring with the magnetic garnet material rod. In some embodiments, the scheelite material can include $(\text{Na}_{0.35}\text{Bi}_{0.65})(\text{Mo}_{0.7}\text{V}_{0.3})\text{O}_4$. In some embodiments, the scheelite material can include $(\text{Na}_{0.2}\text{Bi}_{0.8})(\text{Mo}_{0.4}\text{V}_{0.6})\text{O}_4$.

[0009] Also disclosed herein are embodiments of a method of forming a composite material for use as an isolator or circulator in a radiofrequency device, the method comprising providing a magnetic garnet material rod, providing an outer ring having a scheelite crystalline structure, the outer ring having a firing temperature of 950 °C or below, entering the magnetic garnet material rod within an aperture in the outer ring, and co-firing the outer ring and the magnetic garnet material rod together at a temperature of 950 °C or below to shrink the outer ring around an outer surface of the magnetic garnet material rod without the use of adhesive or glue and form a composite material.

[0010] In some embodiments, the outer ring can have the chemical formula $\text{Li}_{0.05}\text{Bi}_{0.95}\text{Mo}_{0.1}\text{V}_{0.9}\text{O}_4$.

[0011] In some embodiments, the scheelite material can have the chemical formula $\text{Bi}_{1-2x-z}\text{R}_z\text{M}'_x\text{V}_{1-x}\text{M}''_x\text{O}_4$, R being a rare earth element La, Ce, Pr, Sm, Nd, Gd, Dy, Tb, Ho, Er, Tm, Yb, Lu, Y or Sc, M' being Li, Na, or K, and M'' being Mo or W. In some embodiments, the scheelite material can have the chemical formula $(\text{Na},\text{Li})_{0.5x}\text{Bi}_{1-0.5x}(\text{Mo},\text{W})_x\text{V}_{1-x}\text{O}_4$, x being between 0 and 0.5. In some embodiments, the scheelite material can include between 1 and 10 wt. % aluminum oxide. In some embodiments, the scheelite material can include between 2 and 6 wt. % aluminum oxide. In some embodiments, the magnetic garnet material rod can include Bi, Ca, Zr, Y, Fe, and O. In some embodiments, the scheelite material can include BiVO_4 . In some embodiments, the method can further include slicing the composite material.

[0012] Also disclosed herein are embodiments of a radiofrequency isolator or circulator comprising a magnetic garnet material rod, and a ring surrounding the magnetic garnet material rod, the ring being formed from a scheelite material having a firing temperature of 950 °C or below. In some embodiments, the ring can reduce in diameter around the magnetic garnet material rod during firing so that no adhesive is used to connect the ring with the magnetic garnet material rod.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] **Figure 1** illustrates a flow diagram of a method for fabricating composite magnetic-dielectric disc assemblies in accordance with the prior art.

[0014] **Figure 2** schematically shows how materials having one or more features described herein can be designed, fabricated, and used.

[0015] **Figure 3** illustrates a magnetic field v. loss chart.

[0016] **Figures 4A-B** illustrate an embodiment of a composite structure having a ferrite cylinder within a rectangular prism or cylindrical substrate.

[0017] **Figures 5A-B** illustrate an embodiment of a composite tile with a square or circle shape.

[0018] **Figure 6** illustrates an integrated microstrip circulator without a magnet.

[0019] **Figure 7** illustrates an integrated microstrip circulator with a magnet.

[0020] **Figure 8** illustrates example dielectric constant regimes for certain materials.

[0021] **Figure 9** illustrates intensity graphs for BiVO_4 .

[0022] **Figure 10** illustrates intensity graphs for $\text{Na}_{0.35}\text{Bi}_{0.65}\text{Mo}_{0.7}\text{V}_{0.3}\text{O}_4$ as calcined.

[0023] **Figure 11** illustrates dilatometry testing of scheelite materials.

[0024] **Figure 12** illustrates dilatometry testing of BiVO_4 with 1.2 % Al_2O_3 .

[0025] **Figure 13** illustrates an example of a co-firing cycle.

[0026] **Figure 14** illustrates dilatometry results for $\text{Na}_2\text{BiMg}_2\text{V}_3\text{O}_{12}$.

[0027] **Figure 15** is a schematic diagram of one example of a communication network.

[0028] **Figure 16** is a schematic diagram of one example of a communication link using carrier aggregation.

[0029] **Figure 17A** is a schematic diagram of one example of a downlink channel using multi-input and multi-output (MIMO) communications.

[0030] **Figure 17B** is schematic diagram of one example of an uplink channel using MIMO communications.

- [0031] **Figure 18** illustrates a schematic of an antenna system.
- [0032] **Figure 19** illustrates a schematic of an antenna system with an embodiment of an integrated microstrip circulator.
- [0033] **Figure 20** illustrates a MIMO system incorporating embodiments of the disclosure.
- [0034] **Figure 21** is a schematic diagram of one example of a mobile device.
- [0035] **Figure 22** is a schematic diagram of a power amplifier system according to one embodiment.
- [0036] **Figure 23** illustrates a method of forming a composite integrated microstrip circulator.
- [0037] **Figure 24** illustrates an embodiment of an integrated microstrip circulator for testing.
- [0038] **Figure 25** illustrates a perspective view of a cellular antenna base station incorporating embodiments of the disclosure.
- [0039] **Figure 26** illustrates housing components of a base station incorporating embodiments of the disclosed material.
- [0040] **Figure 27** illustrates a cavity filter used in a base station incorporating embodiments of the material disclosed herein.
- [0041] **Figure 28** illustrates an embodiment of a circuit board including embodiments of the material disclosed herein.

DETAILED DESCRIPTION

[0042] Disclosed herein are embodiments of low firing dielectric materials. These materials can be advantageously co-fired with high dielectric materials to form composites for magnetic-dielectric assemblies, such as for isolator and circulator applications. These assemblies can be then incorporated into radiofrequency applications. Advantageously, embodiments of the disclosed materials can be co-fired without needing any adhesives, such as glue, epoxy or other chemical adhesives. Thus, composites formed out of embodiments of the disclosure can be glue free, epoxy free, or adhesive free.

[0043] Embodiments of the disclosure could advantageously allow for 5G systems, in particular operating at 3 GHz and above, to form integrated architectures which can include different components, such as antennas, circulators, amplifiers, and/or semiconductor based amplifiers. By allowing for the integration of these components onto a single substrate, this can improve the overall miniaturization of the device. In some embodiments, the disclosed devices can be operable at frequencies between about 1.8GHz and about 30GHz. In some embodiments, the disclosed device can be operable at frequencies of greater than about 1, 2, 3, 4, 5, 10, 15, 20, or 25 GHz. In some embodiments, the disclosed device can be operable at frequencies of less than 30, 25, 20, 15, 10, 5, 4, 3, or 2 GHz.

[0044] In some embodiments, the integrated architecture can include a directional coupler and/or isolator in a package size which is not much larger than a standard isolator. In some embodiments, the integrated architecture can include a high power switch. In addition to using the dielectric tile as the substrate for the impedance transformer, it could also be used as the substrate for the coupler, switch and termination

[0045] **Figure 2** schematically shows how one or more chemical elements (block **1**), chemical compounds (block **2**), chemical substances (block **3**) and/or chemical mixtures (block **4**) can be processed to yield one or more materials (block **5**) having one or more features described herein. In some embodiments, such materials can be formed into ceramic materials (block **6**) configured to include a desirable dielectric property (block **7**), a magnetic property (block **8**).

[0046] In some embodiments, a material having one or more of the foregoing properties can be implemented in applications (block **10**) such as radio-frequency (RF) application. Such applications can include implementations of one or more features as described herein in devices **12**. In some applications, such devices can further be implemented in products **11**. Examples of such devices and/or products are described herein.

Microstrip Circulators/Isolators

[0047] Circulators are passive multiport devices which can receive and transmit different signals, such as microwave or radiofrequency (RF). These ports can be an external waveguide or transmission line which connects to and from the circulator. Isolators are

similar to circulators, but one or more of the ports can be blocked off. Hence, circulator and isolator can be used interchangeably herein as they can be similar in general structural. Thus, all discussion below can apply both to circulators and isolators.

[0048] Microstrip circulators and isolators are devices known in the art consist of a thin film circuit deposited over a substrate, such as a dielectric ferrite substrate. In some embodiments, one or more ferrite discs can be adhered onto the substrate. Magnet(s) can then be further attached to circulate a signal through the ferrite disc.

[0049] Further, all-ferrite microstrip circulators have been used as well, in particular for radar T/R modules. Circuitry can be printed onto the all ferrite microstrip circulator and a magnet can be added on top to direct the signal. For example, a metallization pattern is formed onto a ferrite substrate. Typically, the metallization pattern consists of a central disc and multiple transmission lines.

[0050] Circulators generally can operate in either of the above or below resonance operating regions. This is shown in **Figure 3**. In some embodiments, above-resonance frequencies can be advantageous for narrow band, sub 4GHz circulators. For higher frequencies, the below resonance region can be more advantageous.

[0051] Microstrip circulators in particular typically work in the below resonance operating region. They use a very small magnet or can be self-biased, such as in the case of hexagonal ferrites. However, square tiles can be a difficult shape to magnetize uniformly, in particular for the all-ferrite microstrip circulators known in the art. Thus, they will operate close to the low field loss region. When transformers are mounted on the lossy unmagnetized ferrite, performance suffers. Further, increased power will make the poor performance even more known. Thus, circulators known in the art suffer from issues due to the ferrite tile being poorly magnetized, leading to poor insertion loss and intermodulation distortion (IMD), and power performance.

Co-Fired Microstrip Circulators/Isolators

[0052] Embodiments of the disclosure can improve overall magnetization and reduce performance issues that can occur for currently known microstrip circulators. Generally, the microstrip circulators can be formed by embedding a ferrite disc, such as an

oxide ferrite disc made of YIG, directly into a dielectric substrate. The combination can then be co-fired together to form a more solid composite structure. Additionally circuitry, such as formed from silver or other metalized substances, can be added. Without the co-firing process, circuit metallization would not be able to be applied. Embodiments of this disclosure can alleviate some of the significant problems of the art.

[0053] Any number of different ferrite disc materials that can be used. In some embodiments, the saturation magnetization levels of the ferrite disc material can range between 1000-5000 (or about 1000 – about 5000) gauss.

[0054] Further, any number of different dielectric substrates known in the art can be used. The dielectric can be formed from dielectric powder or low temperature co-fired ceramic (LTCC) tape. In some embodiments, the dielectric constant can be above 6, 10, 15, 20, 25, 30, 40, 50, or 60. In some embodiments, the dielectric constant can range from 6-30 (or about 6 to about 30). In some embodiments, the dielectric constant can be below about 60, 50, 40, 30, 25, 20, 15, or 10.

[0055] In particular, to form the composite microstrip circulator **100**, a magnetic oxide disc **102**, or other magnetic disc, can be inserted into an aperture of a dielectric substrate **104** as shown in **Figures 4A-B**. In some embodiments, the disc **102** can be a cylindrical rod, though the particular shape is not limiting. The disc **102** can be green, previously fired, or not-previously fired.

[0056] Further, the substrate **104** can generally be a rectangular prism as shown in **Figure 4A**, but other shapes can be used as well such as the cylinder shown in **Figure 4B**. Embodiments of the substrate **104** are disclosed in more detail below. Once the disc **102** is inside the substrate **104**, the components can be co-fired together, using such a method as discussed in U.S. Pat. No. 7,687,014, hereby incorporated by reference in its entirety and discussed below. This co-firing process, further detailed below, can cause the substrate **104** to shrink around the disc **102** and hold it in place in conjunction with adhesives to form the composite structure **100**. This composite structure **100** can then be sliced to form the chip structure as shown in **Figures 5A-B** (**Figure 5A** showing the rectangular prism slice and **Figure 5B** showing the cylinder slice). However, in some embodiments, slicing is not performed and the components are co-fired together at their final thickness. In some

embodiments, a plurality of different discs can be inserted into a single substrate in a plurality of different apertures.

[0057] Thus, in some embodiments a magnetic oxide disk can be co-fired into a square or rectangular dielectric substrate, or any other shaped substrate, which can then serve as a platform for other components, such as circuitry. This composite structure can then be magnetized to serve as a microstrip circulator and/or isolator package, for example, or the ferrite disc could have been magnetized prior to insertion. In some embodiments, the ferrite disc can be magnetized prior to the co-firing step.

[0058] Once the composite structure is formed, other components can be added onto the substrate, such as additional thin film circuits and the like. Thus, embodiments of the disclosure can form an integrated solution which can include a directional coupler and/or isolator in a package size which is not much larger than a standard isolator. Further, advantageously loss may not be affected by the level of magnetic field, or can at least be reduced. In some embodiments, the disclosed circulator will be no larger (and depending on the ferrite/dielectric combination chosen could be smaller) than all current ferrite microstrip circulators.

[0059] Thus, using a co-firing process, a ferrite disc can be embedded into a dielectric tile, as shown in **Figures 5A-B**. The thin ferrite disc shown in the figure can be significantly easier to magnetize uniformly than a square, or other oddly shaped piece, known in the art. In some embodiments, the dielectric tile could be about 25mm square though the particular dimensions are not limiting. This can be used in the 3-4 (or about 3 – about 4) GHz region.

[0060] Using the dielectric tile, a transformer can then be produced as shown in **Figure 6**. As shown, the substrate **104** has space left over for other component attachments. After forming the transformer, only a small magnet needs to be placed on the tile, as shown in **Figure 7**. Thus, assembly time can be much shorter than previously done.

[0061] In addition to using the dielectric tile as the substrate for the impedance transformer, it could also be used as the substrate for the coupler, switch, and termination. Thus, a number of other components can be added onto the substrate after co-firing, reducing

the overall footprint of the device. Further, circuit metallization could be added, but only after the device has been co-fired.

Low Temperature Firing Dielectric Materials for Rings

[0062] Embodiments of the disclosure can be particularly advantageous for a co-firing process with a magnetic material, such as for the formation of circulators/isolators. In particular, they can be high dielectric magnetic materials with low firing temperatures (e.g., they can be fireable at a low temperature). Specifically, a rod of magnetic material, such as a nickel-zinc-ferrite material, magnesium ferrite, or other high saturation magnetization spinel ferrite and/or low firing magnetic garnet material with a high dielectric constant, such as a bismuth containing yttrium iron garnet derivative, can be inserted into an unfired ring formed from embodiments of the disclosed low temperature firing dielectric materials, such as shown in **Figures 4A-B** above (**104** being the ring and **102** being the rod). The high dielectric constant magnetic garnet material can have a dielectric constant of between 24 and 35, such as 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, or 35, but the particular dielectric constant is not limiting. The ring can be any of the materials discussed below, such as scheelite, garnet, etc.

[0063] The combination of the ring and the rod can then be co-fired together so that the ring shrinks around the rod. Both of these materials can be “fireable”, meaning they have the ability to be fired or sintered in an oven/kiln/other heating device, for example to a high density. In some embodiments, firing can change one or more properties of the material, such as the ceramic materials discussed herein. After firing, the combination of ring and rod can be sliced/cut into individual components. Embodiments of these assemblies can be used as isolators and/or circulators for radiofrequency applications, such as for 5G applications.

[0064] Advantageously, this co-firing process can be performed without the use of adhesives/epoxies/glues, or other organic (e.g., carbon-based) polymeric materials, and thus can be considered a “glueless assembly”. For example, a “glue” is not needed to connect the rod to the ring. Previous iterations of the assembly fire the fireable ring separate from the fireable rod due to the temperature for firing the ring being too high, which can lead to melting, or at least considerably damaging the properties of the internal rod. Either both segments can be fired separately, or the ring can be fired first and then the ring/rod assembly

is fired together. For each of these approaches, the ring will not sufficiently shrink around the rod and thus an adhesive will be needed to keep the ring and the rod attached to one another.

[0065] However, the use of adhesives has a number of drawbacks, and advantageously the disclosed material can form a composite structure without the need for such adhesive as the rod and ring can be co-fired together. For example, it is extremely difficult, if not impossible, to metallize the assembly once there is adhesive. This is because the temperature required for metallization is much higher than the use temperature for the adhesive, causing the adhesive to melt and/or lose adhesive.

[0066] Further, the glue is lossy, increasing the insertion loss of glued components. The dielectric loss of the glue at high frequencies is greater than the magnetic or the dielectric material.

[0067] In some embodiments, the material can have ϵ' of less than 10 (or less than about 10). Thus, embodiments of the disclosure can be used for 5G below resonance applications. It can be advantageous to avoid moding and to offset the impedance effect of thinner substrates also used at high frequencies. Accordingly, values below 10 (or below about 10) are used for above 20 GHz frequencies.

[0068] As an example, embodiments of the material as a ring can be suitable for co-firing with a rod material of high magnetization spinels (for example nickel zinc ferrites) such as disclosed in U.S. Pat. Pub. No. 2017/0098885, hereby incorporated by reference in its entirety, in particular for high frequency (5G) applications. Additionally, the ring material can be co-fired with high dielectric constant materials such as disclosed in U.S. Pat. Pub. No. 2018/0016155, the entirety of which is hereby incorporated by reference in its entirety. The high dielectric constant magnetic rod can be a bismuth substituted high dielectric constant magnetic garnet. Standard bismuth doped high dielectric constant garnet materials such as Bi containing garnet materials described in numerous previous patent applications. Y-Bi-Ca-Zr-V-Fe-O sinters around 950 °C. Thus, disclosed herein are ways to lower the firing temperature of scheelite material so that it can be co-fired with the nickel zinc ferrite at an appropriate temperature range.

[0069] As mentioned, the co-fireable ring material can be based on a scheelite structure or scheelite style material (e.g., a crystalline compound which contains a scheelite

atomic arrangement). This can include crystalline compounds which contain a scheelite atomic arrangement, and the term scheelite structure, scheelite, or scheelite style material can be used interchangeably. **Figure 8** illustrates dielectric constant regimes by material family for low firing (<800 °C) oxides. In some embodiments, the scheelite material have the chemical formula BiVO_4 .

[0070] In some embodiments, the material having the scheelite structure can be $\text{Bi}_{1-2x-z}\text{R}_z\text{M}'_x\text{V}_{1-x}\text{M}''_{2x}\text{O}_4$ where R is a rare earth element La, Ce, Pr, Sm, Nd, Gd, Dy, Tb, Ho, Er, Tm, Yb, Lu, Y or Sc, M' is Li, Na, or K and M'' is Mo or W. In some embodiments, $0 < z < 0.7$ and $0 < x < 0.5$.

[0071] In some embodiments, the scheelite material can have the chemical formula $(\text{Na}, \text{Li})_{0.5x}\text{Bi}_{1-0.5x}(\text{Mo}, \text{W})_x\text{V}_{1-x}\text{O}_4$. In some embodiments, $0 < x < 0.5$.

[0072] In some embodiments, scheelites may have a low firing temperature (< 850 °C, < 900 °C) a low dielectric loss tangent (<.001 at 3GHz), and with suitable substitutions into the structure may exhibit a range of dielectric constants from 8 to 70 (or about 8 to about 70), between 10 and 60 (or about 10 to about 60), between 20 and 50 (or about 20 and about 50), or between 30 and 40 (or between about 30 and about 40). In some embodiments, the scheelites may exhibit a dielectric constant of 8, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, or 70 (or about 8, about 10, about 15, about 20, about 25, about 30, about 35, about 40, about 45, about 50, about 55, about 60, about 65, or about 70).

[0073] The scheelite material in particular can be used as a low dielectric constant co-fireable material to fire with high dielectric constant materials, for example garnet and/or Bi doped materials, or any of the high magnetic rod materials discussed herein. It can be advantageous to use this material to avoid moding, and to offset the impedance effect of thinner substrates also necessary at high frequencies. The scheelite material can further be particularly useful for high frequency microstrip or surface integrated waveguide designs, for example due to the lowered temperature which allows for chemical compatibility and a wider range of dielectric constants.

[0074] In some embodiments, aluminum oxide, such as Al_2O_3 , can be added into the ring materials, such as the scheelite material, garnet material, spinel material, pyrochlore material, etc. discussed herein. For example, the aluminum oxide can be blended into the ring

material as aluminum oxide, such as by combining different powders. In some embodiments, 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 (or about 1, about 2, about 3, about 4, about 5, about 6, about 7, about 8, about 9, or about 10) wt. % of aluminum oxide can be incorporated into the scheelite material. In some embodiments, 1.2 (or about 1.2) wt. % of aluminum oxide can be incorporated into the scheelite material. In some embodiments, greater than 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 (or about 1, about 2, about 3, about 4, about 5, about 6, about 7, about 8, about 9, or about 10) wt. % of aluminum oxide can be incorporated into the scheelite material. In some embodiments, less than 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 (or about 1, about 2, about 3, about 4, about 5, about 6, about 7, about 8, about 9, or about 10) wt. % of aluminum oxide can be incorporated into the scheelite material. In some embodiments, between 2 and 6 (or between about 2 and about 6) wt. % of aluminum oxide can be incorporated into the scheelite material. In some embodiments, 1-10 wt. % (or about 1 to about 10 wt. %) aluminum oxide can be added into the scheelite material. The incorporation of aluminum oxide can regulate thermal expansion behavior and prevent cracking. For example, it can allow the scheelite material to better match a thermal expansion material of a high dielectric, such as a bismuth rich high dielectric constant garnet, as compared to undoped scheelite material, thereby allowing for successful co-firing without cracking. Specifically, the cracking can be prevented by regulating thermal expansion.

[0075] Table 1 illustrates a number of different scheelite materials and their properties. In some embodiments, tungstates can have lower dielectric constants than corresponding molybdates, both of which can have a scheelite structure.

Table 1: Scheelite Materials

Composition	Firing Temp. (°C)	Dielectric Constant	Q	τ_f (ppm/°C)
$(K_{0.5}La_{0.5})MoO_4$	680	10.3	59000	-81
$LiKSm_2(MoO_4)_4$	620	11.5	39000	-16
$(Li_{0.5}Sm_{0.5})MoO_4$	640	19.9	4570	+231
$(Li_{0.5}Nd_{0.5})MoO_4$	660	20.3	3000	+235

$(\text{Li}_{0.5}\text{Ce}_{0.5})\text{MoO}_4$	580	20.6	1990	+228
$(\text{Ag}_{0.5}\text{Bi}_{0.5})(\text{Mo}_{0.5}\text{W}_{0.5})\text{O}_4$	500	26.3	10000	+20
$(\text{Li}_{0.5}\text{Bi}_{0.5})\text{WO}_4$	650	26.5	16400	+70
$(\text{Ag}_{0.5}\text{Bi}_{0.5})\text{MoO}_4$	690	30.4	12600	+52
$(\text{Li}_{0.5}\text{Bi}_{0.5})(\text{Mo}_{0.4}\text{W}_{0.6})\text{O}_4$	620	31.5	8500	+20
$(\text{Na}_{0.5}\text{Bi}_{0.5})\text{MoO}_4$	690	34.4	12300	+43
$(\text{K}_{0.5}\text{Bi}_{0.5})\text{MoO}_4$	630	37.0	4000	+117
$(\text{Na}_{0.35}\text{Bi}_{0.65})(\text{Mo}_{0.7}\text{V}_{0.3})\text{O}_4$	680	44.0	6100	N/A
$(\text{Li}_{0.5}\text{Bi}_{0.5})\text{MoO}_4$	560	44.4	3200	N/A
$(\text{Na}_{0.275}\text{Bi}_{0.725})(\text{Mo}_{0.55}\text{V}_{0.45})\text{O}_4$	700	51	5500	N/A
$(\text{Na}_{0.2}\text{Bi}_{0.8})(\text{Mo}_{0.4}\text{V}_{0.6})\text{O}_4$	700	58	5000	N/A
$(\text{Li}_{0.05}\text{Bi}_{0.95})(\text{Mo}_{0.1}\text{V}_{0.9})\text{O}_4$	650	81	1000	N/A

[0076] In some embodiments, the disclosed scheelite material can have a Q range of greater than 900, 1000, 1100, 1200, or 1300 (or greater than about 900, about 1000, about 1100, about 1200, or about 1300). In some embodiments, the disclosed scheelite material can have a Q range of less than 900, 1000, 1100, 1200, or 1300 (or less than about 900, 1000, 1100, 1200, or 1300).

[0077] In some embodiments, the disclosed scheelite material can have a dielectric constant of between 10 and 100 (or between about 10 and about 100). In some embodiments, the disclosed scheelite material can have a dielectric constant of greater than 10, 20, 30, 40, 50, 60, 70, 80, 90, or 100 (or greater than about 10, about 20, about 30, about 40, about 50, about 60, about 70, about 80, about 90, or about 100). In some embodiments, the disclosed scheelite material can have a dielectric constant of less than 20, 30, 40, 50, 60, 70, 80, 90, or 100 (or less than about 20, about 30, about 40, about 50, about 60, about 70, about 80, about 90, or about 100).

[0078] In some embodiments, the disclosed scheelite material can have a firing temperature of below 900, 850, 800, or 750 °C (or below about 900, about 850, about 800, or about 750 °C). In some embodiments, the disclosed scheelite material can have a firing temperature of greater than 900, 850, 800, or 750 °C (or greater than about 850, about 800, or about 750 °C). In some embodiments, the disclosed scheelite material can have a firing temperature of 775 °C (or about 775 °C).

[0079] Table 2 illustrates experimental results of using a scheelite material. Further, Table 2 discloses potential device application for the scheelite materials.

Table 2: Scheelite Experimental Results

Material	Dielectric Constant	Firing Temperature, °C	QF Product, THz	Device Application
$\text{Na}_{0.2}\text{Bi}_{0.8}\text{Mo}_{0.4}\text{V}_{0.6}\text{O}_4$	56.33	725	4.157	Triplate above resonance or below resonance; Microstrip below resonance
$\text{Li}_{0.05}\text{Bi}_{0.95}\text{Mo}_{0.1}\text{V}_{0.9}\text{O}_4$	73.23	750	4.921	Triplate above resonance or below resonance; Microstrip below resonance
$(\text{Li}_{0.5}\text{Bi}_{0.5})(\text{Mo}_{0.4}\text{W}_{0.6})\text{O}_4$	30	?	?	Triplate below resonance; Microstrip below resonance
$(\text{Na}_{0.5}\text{Bi}_{0.5})\text{MoO}_4$	16.19	700	3.288	Substrate Integrated Waveguides (SIW)

				below resonance
$\text{Na}_{0.35}\text{Bi}_{0.65}\text{Mo}_{0.7}\text{V}_{0.3}\text{O}_4$	43	750		Triplate above resonance or below resonance; Microstrip below resonance

[0080] Table 3 illustrates particular scheelite based compositions which can be advantageously co-fired with TTHiE high dielectric materials.

Table 3: Scheelite based TTHiE Co-Fired Compositions

Material	Expected Dielectric Constant	MS	Firing Temp. °C	Soak (hr)	Fired Density	ϵ'	Q	f_0	OD Shrinkage	Length Shrinkage
$\text{Na}_{0.2}\text{Bi}_{0.8}\text{Mo}_{0.4}\text{V}_{0.6}\text{O}_4$										
$\text{Li}_{0.05}\text{Bi}_{0.95}\text{Mo}_{0.1}\text{V}_{0.9}\text{O}_4$	70	1429561	750	4	6.454	73.23	1584	3107.7	8.10%	7.23%
$\text{Li}_{0.5}\text{Bi}_{0.5}\text{Mo}_{0.4}\text{W}_{0.6}\text{O}_4$	30									
$\text{Na}_{0.5}\text{Bi}_{0.5}\text{MoO}_4$	20	1429563	700	4	4.431	16.19	508	6473.3	4.52%	3.38%
$\text{Na}_2\text{BiMg}_2\text{V}_3\text{O}_{12}$	25	1429562	750	4	4.178	24.04	807	5359.1	8.10%	7.76%
$\text{Na}_{0.35}\text{Bi}_{0.65}\text{Mo}_{0.7}\text{V}_{0.3}\text{O}_4$	43		725	4					12.28%	11.29%
$\text{Na}_{0.35}\text{Bi}_{0.65}\text{Mo}_{0.7}\text{V}_{0.3}\text{O}_4$	43		725	4					10.93%	12.50%
BiVO_4	80		700	4	5.074				11.95%	11.17%
BiVO_4	80		700	4	4.926				10.82%	11.43%
BiVO_4	80		800	4	6.605				19.26%	18.39%
BiVO_4	80		800	4	6.554				18.94%	18.39%
BiVO_4	80		850	4	6.605	40			19.09%	17.39%
BiVO_4	80		850	4	6.610				19.09%	17.97%

$\text{Na}_{0.35}\text{Bi}_{0.65}\text{Mo}_{0.7}\text{V}_{0.3}\text{O}_4$	43		725	4					12.28%	11.29%
$\text{Na}_{0.35}\text{Bi}_{0.65}\text{Mo}_{0.7}\text{V}_{0.3}\text{O}_4$	43		725	4					10.93%	12.50%
$\text{Na}_{0.35}\text{Bi}_{0.65}\text{Mo}_{0.7}\text{V}_{0.3}\text{O}_4$	43		750	4					14.92%	15.09%
$\text{Na}_{0.35}\text{Bi}_{0.65}\text{Mo}_{0.7}\text{V}_{0.3}\text{O}_4$	43		750	4					13.73%	13.29%
$\text{Na}_{0.35}\text{Bi}_{0.65}\text{Mo}_{0.7}\text{V}_{0.3}\text{O}_4$	43		750	4	4.77				13.81%	13.29%
$\text{Na}_{0.35}\text{Bi}_{0.65}\text{Mo}_{0.7}\text{V}_{0.3}\text{O}_4$	43		750	4	4.80				13.73%	13.74%

[0081] As shown above, bismuth vanadate (BiVO_4) can be a particularly useful scheelite material. In some embodiments, sodium or molybdenum can be added into the material.

[0082] Table 4 illustrates other examples of materials having a scheelite structure which may be useful for co-firing.

Table 4: Materials Having Scheelite Structure

Scheelite	Dielectric Constant	Firing Temperature (°C)
$\text{Na}_{0.2}\text{Bi}_{0.8}\text{Mo}_{0.4}\text{V}_{0.6}\text{O}_4$	57	675
$\text{Li}_{0.05}\text{Bi}_{0.95}\text{Mo}_{0.1}\text{V}_{0.9}\text{O}_4$	70	675
$\text{Li}_{0.5}\text{Bi}_{0.5}\text{Mo}_{0.4}\text{W}_{0.6}\text{O}_4$	30	600
$\text{Li}_{0.5}\text{Sm}_{0.5}\text{MoO}_4$	25	640

[0083] **Figure 9** illustrates an x-ray diffraction trace for BiVO_4 . **Figure 10** illustrates intensity graphs for $\text{Na}_{0.35}\text{Bi}_{0.65}\text{Mo}_{0.7}\text{V}_{0.3}\text{O}_4$ as calcined. Both figures indicate that the material has a scheelite structure and only a scheelite structure is present.

[0084] **Figure 11** illustrates a dilatometry testing of scheelite materials. The TTHIE-1950 is a Bi-Ca-Zr-Y-Fe-O material. It can be advantageous for the mean alpha of the non-TTHIE materials to match as closely as possible to the mean alpha of the TTHiE material, such as U.S. Pat. No. 9,263,175 and 9,527,776, the entirety of each of which is hereby incorporated by reference in its entirety.

[0085] **Figure 12** illustrates dilatometry testing of BiVO_4 with 1.2% Al_2O_3 . As shown, the thermal expansion coefficient is a reasonable value to be co-fired with magnetic materials.

[0086] In some embodiments, the disclosed scheelite material can have a mean alpha within 1%, 5%, or 10% (or within about 1%, about 5%, or about 10%) of the TTHI material. In some embodiments, the mean alpha can be in the range of 6 – 13 (or about 6 – about 13) ppm/degree C, such as 6, 7, 8, 9, 10, 11, 12, or 13 (or about 6, about 7, about 8, about 9, about 10, about 11, about 12, or about 13) ppm/degree C.

[0087] **Figure 13** illustrates the co-fire ideal cycle with garnet and dielectric factors. The ideal is that the OD of the pre-fired garnet rod is exactly (or about exactly) the same as the ID of the pressed dielectric tube at the end of the co-firing phase, but before cooling. Since the garnet has a fixed expansion, this is done by adjusting the shrinkage and initial size of the dielectric, thru control of green density. Diffusion occurs at the co-fire temperature after the garnet and dielectric are in contact, forming a bond; too much diffusion may cause dielectric loss. The garnet and dielectric remain in contact thru cooling, because their expansion (contraction) coefficients are the same, retaining the bond.

[0088] In some embodiments, other ring materials can be used for co-firing instead of scheelites, with or without the aluminum oxide discussed above. For example, spinels structures can be used as well. Table 5 illustrates potential spinel materials that can be used.

Table 5: Garnet Materials for Co-firing

Composition	Firing Temperature (°C)	Dielectric Constant	Qf product (THz)	t _F (ppm/°C)
Na_2MoO_4	600	4.1	46.9	-76
Li_2MoO_4	540	5.5	59.8	-160
Li_2WO_4	640	5.5	97.3	-146
LiMgVO_4	700	8.9	23.8	-140

[0089] Other useful ring materials can be garnets, with or without the aluminum oxide discussed above, which are isostructural with the high dielectric nickel materials discussed above. Table 6 illustrates potential garnet materials.

Table 6: Spinel Materials for Co-firing

Composition	Firing Temp. (°C)	Dielectric Constant	Qf product (THz)	t _F (ppm/°C)
Li _{0.16} Na _{0.84} Ca ₂ Mg ₂ V ₃ O ₁₂	920	9.9	45.5	+2
LiCa ₃ MgV ₃ O ₁₂	900	10.5	74.7	-61
LiMg ₄ V ₃ O ₁₂	740	10.7	24.0	-11.7
LiCa ₃ ZnV ₃ O ₁₂	900	11.5	81.1	-72
Na ₂ YMg ₂ V ₃ O ₁₂	850	12.3	23.2	-4.1
NaMg ₄ V ₃ O ₁₂	690	12.5	35.9	-58.1
Na ₂ BiMg ₂ V ₃ O ₁₂	750	24?	4.4	

[0090] Figure 14 illustrates dilatometry results for Na₂BiMg₂V₃O₁₂.

[0091] Another useful ring material can include pyrochlore materials, with or without the aluminum oxide discussed above. Table 7 illustrates potential pyrochlore materials which can be used.

Table 7: Pyrochlore Materials for Co-firing

Composition	Firing Temp. (°C)	Dielectric Constant	Qf product (THz)	t _F (ppm/°C)
(Bi _{1.92} Zn _{0.08})(Zn _{0.64} Nb _{1.36})O ₇	1000	75.0	1800	
(Bi _{1.92} Ca _{0.08})(Zn _{0.64} Nb _{1.36})O ₇	960	76.0	3900	
Bi ₂ (Zn _{1/3} Nb _{2/3-x} V _x)O ₇ (x = .001-.003)	850	78.5	3780	

$\text{Bi}_{18}(\text{Zn}_{0.725}\text{Ca}_{0.275})_8\text{Nb}_{12}\text{O}_{65}$	925	79	1000	+3.2
$\text{Bi}_3(\text{Nb}_{0.9}\text{V}_{0.1})\text{O}_7$	870	80	600	-22
$\text{Bi}_2(\text{Zn}_{0.5}\text{Mg}_{0.5})_{2/3}\text{Nb}_{4/3}\text{O}_7$	900	98.0	3000	
$\text{Bi}_{1.5}\text{Zn}_{0.92}\text{Nb}_{1.5}\text{O}_{6.92}$ + 0.6% V_2O_5	850	148.0	120	

[0092] In some embodiments, higher energy comminution can reduce the firing temperatures to around 850 °C, or 850 °C or below by increasing the surface area of the powder making it more reactive. In some embodiments, the pyrochlore materials can have a dielectric constant range of 60-100.

[0093] Table 8 illustrates device applications for co-fire ferrite/dielectric combinations. It will be understood that the below table shows examples only, and the disclosure is not limited to the particular devices shown below.

Table 8: Example Uses of Co-Fired Materials

Ferrite	Dielectric's dielectric constant	RF Device Transmission line	Operating mode, above or below FMR	Frequency Range	Co-fire Functional Requirement
Conventional Garnet, 1200 to 1950 Gauss	20-30	Stripline	Above	600 MHz to ~3.5 GHz	Replace Production ID grind/glue; allow metallization
Spinel, up to 5000 Gauss	8-20	SIW, Microstrip	Below	10-60+ GHz	5G component compatibility,

					subsystem integration
TTHiE, 1150-1950 Gauss	45-120+	Stripline	Above	600 MHz to ~3.5 GHz	Replace Production ID grind/glue; allow metallization
TTHiE 400-1950 Gauss	20-30; 45-120+	Stripline, Microstrip	Below	1.8-6GHz	5G components/ subsystem integration

5G Applications

[0094] Embodiments of the disclosed composite microstrip circulators can be particularly advantageous for 5th generation wireless system (5G) applications, though could also be used for early 4G and 3G applications as well. 5G technology is also referred to herein as 5G New Radio (NR). 5G networks can provide for significantly higher capacities than current 4G system, which allows for a larger number of consumers in an area. This can further improve uploading/downloading limits and requirements. In particular, the large number of circulators, such as those described herein, needed for 5G (typically 1 per front end module or FEM) requires further integration of components. The disclosed embodiments of circulators can allow for this integration and thus can be particularly advantageous. Other components in the front end module will be microstrip or SMT based.

[0095] Preliminary specifications for 5G NR support a variety of features, such as communications over millimeter wave spectrum, beam forming capability, high spectral efficiency waveforms, low latency communications, multiple radio numerology, and/or non-orthogonal multiple access (NOMA). Although such RF functionalities offer flexibility to networks and enhance user data rates, supporting such features can pose a number of technical challenges.

[0096] The teachings herein are applicable to a wide variety of communication systems, including, but not limited to, communication systems using advanced cellular technologies, such as LTE-Advanced, LTE-Advanced Pro, and/or 5G NR.

[0097] **Figure 15** is a schematic diagram of one example of a communication network **10**. The communication network **10** includes a macro cell base station **1**, a mobile device **2**, a small cell base station **3**, and a stationary wireless device **4**.

[0098] The illustrated communication network **10** of **Figure 15** supports communications using a variety of technologies, including, for example, 4G LTE, 5G NR, and wireless local area network (WLAN), such as Wi-Fi. Although various examples of supported communication technologies are shown, the communication network **10** can be adapted to support a wide variety of communication technologies.

[0099] Various communication links of the communication network **10** have been depicted in **Figure 15**. The communication links can be duplexed in a wide variety of ways, including, for example, using frequency-division duplexing (FDD) and/or time-division duplexing (TDD). FDD is a type of radio frequency communications that uses different frequencies for transmitting and receiving signals. FDD can provide a number of advantages, such as high data rates and low latency. In contrast, TDD is a type of radio frequency communications that uses about the same frequency for transmitting and receiving signals, and in which transmit and receive communications are switched in time. TDD can provide a number of advantages, such as efficient use of spectrum and variable allocation of throughput between transmit and receive directions.

[0100] As shown in **Figure 15**, the mobile device **2** communicates with the macro cell base station **1** over a communication link that uses a combination of 4G LTE and 5G NR technologies. The mobile device **2** also communicates with the small cell base station **3** which can include embodiments of the disclosure. In the illustrated example, the mobile device **2** and small cell base station **3** communicate over a communication link that uses 5G NR, 4G LTE, and Wi-Fi technologies.

[0101] In certain implementations, the mobile device **2** communicates with the macro cell base station **2** and the small cell base station **3** using 5G NR technology over one

or more frequency bands that are less than 6 Gigahertz (GHz). In one embodiment, the mobile device **2** supports a HPUE power class specification.

[0102] The illustrated small cell base station **3**, incorporating embodiments of the disclosure, also communicates with a stationary wireless device **4**. The small cell base station **3** can be used, for example, to provide broadband service using 5G NR technology over one or more frequency bands above 6 GHz, including, for example, millimeter wave bands in the frequency range of 30 GHz to 300 GHz.

[0103] In certain implementations, the small cell base station **3** communicates with the stationary wireless device **4** using beamforming. For example, beamforming can be used to focus signal strength to overcome path losses, such as high loss associated with communicating over millimeter wave frequencies.

[0104] The communication network **10** of **Figure 15** includes the macro cell base station **1**, which can include embodiments of the disclosure, and the small cell base station **3**. In certain implementations, the small cell base station **3** can operate with relatively lower power, shorter range, and/or with fewer concurrent users relative to the macro cell base station **1**. The small cell base station **3** can also be referred to as a femtocell, a picocell, or a microcell.

[0105] Although the communication network **10** is illustrated as including two base stations, the communication network **10** can be implemented to include more or fewer base stations and/or base stations of other types.

[0106] The communication network **10** of **Figure 15** is illustrated as including one mobile device and one stationary wireless device. The mobile device **2** and the stationary wireless device **4** illustrate two examples of user devices or user equipment (UE). Although the communication network **10** is illustrated as including two user devices, the communication network **10** can be used to communicate with more or fewer user devices and/or user devices of other types. For example, user devices can include mobile phones, tablets, laptops, IoT devices, wearable electronics, and/or a wide variety of other communications devices.

[0107] User devices of the communication network **10** can share available network resources (for instance, available frequency spectrum) in a wide variety of ways.

[0108] Enhanced mobile broadband (eMBB) refers to technology for growing system capacity of LTE networks. For example, eMBB can refer to communications with a peak data rate of at least 10Gbps and a minimum of 100Mbps for each user device. Ultra-reliable low latency communications (uRLLC) refers to technology for communication with very low latency, for instance, less than 2 ms. uRLLC can be used for mission-critical communications such as for autonomous driving and/or remote surgery applications. Massive machine-type communications (mMTC) refers to low cost and low data rate communications associated with wireless connections to everyday objects, such as those associated with Internet of Things (IoT) applications.

[0109] The communication network **10** of **Figure 15** can be used to support a wide variety of advanced communication features, including, but not limited to eMBB, uRLLC, and/or mMTC.

[0110] A peak data rate of a communication link (for instance, between a base station and a user device) depends on a variety of factors. For example, peak data rate can be affected by channel bandwidth, modulation order, a number of component carriers, and/or a number of antennas used for communications.

[0111] For instance, in certain implementations, a data rate of a communication link can be about equal to $M \cdot B \cdot \log_2(1 + S/N)$, where M is the number of communication channels, B is the channel bandwidth, and S/N is the signal-to-noise ratio (SNR).

[0112] Accordingly, data rate of a communication link can be increased by increasing the number of communication channels (for instance, transmitting and receiving using multiple antennas), using wider bandwidth (for instance, by aggregating carriers), and/or improving SNR (for instance, by increasing transmit power and/or improving receiver sensitivity).

[0113] 5G NR communication systems can employ a wide variety of techniques for enhancing data rate and/or communication performance.

[0114] **Figure 16** is a schematic diagram of one example of a communication link using carrier aggregation. Carrier aggregation can be used to widen bandwidth of the communication link by supporting communications over multiple frequency carriers, thereby

increasing user data rates and enhancing network capacity by utilizing fragmented spectrum allocations.

[0115] In the illustrated example, the communication link is provided between a base station **21** and a mobile device **22**. As shown in **Figure 16** the communications link includes a downlink channel used for RF communications from the base station **21** to the mobile device **22**, and an uplink channel used for RF communications from the mobile device **22** to the base station **21**.

[0116] Although **Figure 16** illustrates carrier aggregation in the context of FDD communications, carrier aggregation can also be used for TDD communications.

[0117] In certain implementations, a communication link can provide asymmetrical data rates for a downlink channel and an uplink channel. For example, a communication link can be used to support a relatively high downlink data rate to enable high speed streaming of multimedia content to a mobile device, while providing a relatively slower data rate for uploading data from the mobile device to the cloud.

[0118] In the illustrated example, the base station **21** and the mobile device **22** communicate via carrier aggregation, which can be used to selectively increase bandwidth of the communication link. Carrier aggregation includes contiguous aggregation, in which contiguous carriers within the same operating frequency band are aggregated. Carrier aggregation can also be non-contiguous, and can include carriers separated in frequency within a common band or in different bands.

[0119] In the example shown in **Figure 16**, the uplink channel includes three aggregated component carriers f_{UL1} , f_{UL2} , and f_{UL3} . Additionally, the downlink channel includes five aggregated component carriers f_{DL1} , f_{DL2} , f_{DL3} , f_{DL4} , and f_{DL5} . Although one example of component carrier aggregation is shown, more or fewer carriers can be aggregated for uplink and/or downlink. Moreover, a number of aggregated carriers can be varied over time to achieve desired uplink and downlink data rates.

[0120] For example, a number of aggregated carriers for uplink and/or downlink communications with respect to a particular mobile device can change over time. For example, the number of aggregated carriers can change as the device moves through the communication network and/or as network usage changes over time.

[0121] With reference to **Figure 16**, the individual component carriers used in carrier aggregation can be of a variety of frequencies, including, for example, frequency carriers in the same band or in multiple bands. Additionally, carrier aggregation is applicable to implementations in which the individual component carriers are of about the same bandwidth as well as to implementations in which the individual component carriers have different bandwidths.

[0122] **Figure 17A** is a schematic diagram of one example of a downlink channel using multi-input and multi-output (MIMO) communications. **Figure 17B** is schematic diagram of one example of an uplink channel using MIMO communications.

[0123] MIMO communications use multiple antennas for simultaneously communicating multiple data streams over common frequency spectrum. In certain implementations, the data streams operate with different reference signals to enhance data reception at the receiver. MIMO communications benefit from higher SNR, improved coding, and/or reduced signal interference due to spatial multiplexing differences of the radio environment.

[0124] MIMO order refers to a number of separate data streams sent or received. For instance, MIMO order for downlink communications can be described by a number of transmit antennas of a base station and a number of receive antennas for UE, such as a mobile device. For example, two-by-two (2x2) DL MIMO refers to MIMO downlink communications using two base station antennas and two UE antennas. Additionally, four-by-four (4x4) DL MIMO refers to MIMO downlink communications using four base station antennas and four UE antennas.

[0125] In the example shown in **Figure 17A**, downlink MIMO communications are provided by transmitting using M antennas **43a**, **43b**, **43c**, ... **43m** of the base station **41** and receiving using N antennas **44a**, **44b**, **44c**, ... **44n** of the mobile device **42**. Accordingly, **Figure 17A** illustrates an example of $M \times N$ DL MIMO.

[0126] Likewise, MIMO order for uplink communications can be described by a number of transmit antennas of UE, such as a mobile device, and a number of receive antennas of a base station. For example, 2x2 UL MIMO refers to MIMO uplink communications using two UE antennas and two base station antennas. Additionally, 4x4 UL

MIMO refers to MIMO uplink communications using four UE antennas and four base station antennas.

[0127] In the example shown in **Figure 17B**, uplink MIMO communications are provided by transmitting using N antennas **44a**, **44b**, **44c**, ... **44n** of the mobile device **42** and receiving using M antennas **43a**, **43b**, **43c**, ... **43m** of the base station **41**. Accordingly, **Figure 17B** illustrates an example of $N \times M$ UL MIMO.

[0128] By increasing the level or order of MIMO, bandwidth of an uplink channel and/or a downlink channel can be increased.

[0129] Although illustrated in the context of FDD, MIMO communications are also applicable communication links using TDD.

[0130] For these 5G networks, one form of base station will be massive multiple input, multiple output (MIMO) based, with an array of perhaps 64-128 antennas capable of multi-beam forming to interact with handheld terminals at very high data rates. Thus, embodiments of the disclosure can be incorporated into the base stations to provide for high capacity applications.

[0131] This approach is similar to radar phased array T/R modules, with individual transceivers for each antenna element, although massive MIMO is not a phased array in the radar sense. The objective is optimum coherent signal strength at the terminal(s) rather than direction finding. Further, signal separation will be time division (TD) based, requiring a means of duplexing/switching to separate Tx and Rx signals

[0132] For discussion, it is assumed that there is one Tx, one Rx module, one duplexing circulator and one antenna filter per antenna. However, other configurations can be used as well.

[0133] **Figure 18** shows a simplified version of an RF transmission system, omitting drivers and switching logic. As shown, the system can include a number of different components, including a circulator. Thus, embodiments of the disclosure can be used as the circulator in the RF system, either for newly created systems or as improved replacements for the previous systems. Specifically, embodiments of the disclosure relate to hybrid solutions using a stripline circulator, and microstrip or stripline topology for the remaining components.

[0134] **Figure 19** illustrates the integrated component of **Figures 5A-B** discussed above onto the simplified RF antenna structure. As shown, the substrate can include the co-fired ferrite/dielectric tile for the circulator. In addition, a coupler, switch, and load can also be applied to the dielectric tile outside of the ferrite. The conductors and the ground plane could be in a thick film silver. In some embodiments, the circulator subassembly can also be integrated with the power amplifier (PA) and low noise amplifier (LNA) modules.

[0135] Embodiments of the disclosure can have advantages over circulators known in the art. For example,

- Couplers and other transmission lines have much lower insertion loss compared with other couplers, such as semiconductor couplers
- Coupling is more consistent
- Loads can dissipate heat more easily compared with soft substrate
- Circulators have lower loss than all-ferrite substrate based devices
- The dielectric is temperature stable, assisting the coupler and circulator's performance
- The size of the devices can be reduced by using higher dielectric constant ceramic dielectric if required

[0136] Further, embodiments of the ceramic circulator can have the following advantages:

- Heat/power dissipation/thermal conductivity for PA and load
- Isotropic dielectric (except TTB) for coupler/filter design
- Range of dielectric constant (4-100+) for size reduction
- Low dielectric loss (coupler/filter)
- Tight dielectric constant tolerance (coupler/filter/antenna)
- Stable dielectric constant over temperature (coupler/filter/circulator)
- Modest Cost

[0137] On the other hand, soft substrate (e.g., softboards) can have the following disadvantages:

- Poor conductivity due to plastic conductivity
- Anisotropic (xy versus z direction)

- Only 3-10 with some, fixed with others
- Higher losses
- Looser tolerances
- Unstable over temperature

[0138] Accordingly, embodiments of the disclosure can have significant advantages over circulators previously known in the art.

[0139] **Figure 20** illustrates another embodiment of a MIMO system that the disclosed microstrip circulators can be incorporated into. With the advent of massive MIMO for 5G system the current antennas will be replaced with antenna arrays with, for example, 64 array elements. Each element can be fed by a separate front end module (FEM).

[0140] **Figure 21** is a schematic diagram of one example of a mobile device **800**. The mobile device **800** includes a baseband system **801**, a transceiver **802**, a front end system **803**, antennas **804**, a power management system **805**, a memory **806**, a user interface **807**, and a battery **808** and can interact with the base stations including embodiments of the microstrip circulators disclosed herein.

[0141] The mobile device **800** can be used communicate using a wide variety of communications technologies, including, but not limited to, 2G, 3G, 4G (including LTE, LTE-Advanced, and LTE-Advanced Pro), 5G NR, WLAN (for instance, Wi-Fi), WPAN (for instance, Bluetooth and ZigBee), and/or GPS technologies.

[0142] The transceiver **802** generates RF signals for transmission and processes incoming RF signals received from the antennas **804**. It will be understood that various functionalities associated with the transmission and receiving of RF signals can be achieved by one or more components that are collectively represented in **Figure 21** as the transceiver **802**. In one example, separate components (for instance, separate circuits or dies) can be provided for handling certain types of RF signals.

[0143] In certain implementations, the mobile device **800** supports carrier aggregation, thereby providing flexibility to increase peak data rates. Carrier aggregation can be used for both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD), and may be used to aggregate a plurality of carriers or channels. Carrier aggregation includes contiguous aggregation, in which contiguous carriers within the same operating frequency

band are aggregated. Carrier aggregation can also be non-contiguous, and can include carriers separated in frequency within a common band or in different bands.

[0144] The antennas **804** can include antennas used for a wide variety of types of communications. For example, the antennas **804** can include antennas associated transmitting and/or receiving signals associated with a wide variety of frequencies and communications standards.

[0145] In certain implementations, the antennas **804** support MIMO communications and/or switched diversity communications. For example, MIMO communications use multiple antennas for communicating multiple data streams over a single radio frequency channel. MIMO communications benefit from higher signal to noise ratio, improved coding, and/or reduced signal interference due to spatial multiplexing differences of the radio environment. Switched diversity refers to communications in which a particular antenna is selected for operation at a particular time. For example, a switch can be used to select a particular antenna from a group of antennas based on a variety of factors, such as an observed bit error rate and/or a signal strength indicator.

[0146] **Figure 22** is a schematic diagram of a power amplifier system **840** according to one embodiment. The illustrated power amplifier system **840** includes a baseband processor **821**, a transmitter **822**, a power amplifier (PA) **823**, a directional coupler **824**, a bandpass filter **825**, an antenna **826**, a PA bias control circuit **827**, and a PA supply control circuit **828**. The illustrated transmitter **822** includes an I/Q modulator **837**, a mixer **838**, and an analog-to-digital converter (ADC) **839**. In certain implementations, the transmitter **822** is included in a transceiver such that both transmit and receive functionality is provided. Embodiments of the disclosed microstrip circulators can be incorporated into the power amplifier system.

Methodology

[0147] Disclosed herein are embodiments of a process for making an integrated microstrip component. **Figure 23** discloses an embodiment of a process **300** that can be used.

[0148] Returning to **Figure 23**, at step **302**, a ferrite disc or cylinder can be formed from a magnetic ceramic material by any suitable conventional process known in the

art for making such elements, i.e., magnetic oxides of the types used in high frequency electronic components. Similarly, at step **304**, a substrate can be formed from a dielectric material by any suitable conventional process. In some embodiments, the ferrite disc can be sintered by firing it in a kiln. Some examples of materials and firing temperatures are set forth below, following this process flow description. However, persons skilled in the art to which the invention relates understand that the materials and processes by which magnetic ceramic and dielectric ceramic elements of this type are made are well known in the art. Therefore, suitable materials and temperatures are not listed exhaustively. All such suitable materials and process for making such rods, cylinders and similar elements of this type are intended to be within the scope of the invention.

[0149] At step **306**, the disc can be combined into the dielectric substrate with the aperture. For example, the outside surface of the disc can be machined to ensure it is of an outside diameter (OD) that is less than the inside diameter (ID) of the substrate aperture. In some embodiments, the OD is slightly smaller than the ID to enable the disc to be inserted into the substrate.

[0150] In some embodiments, the pre-fired disc can be received in an unfired or “green” substrate to form the composite assembly **100** shown in **Figures 4A-B**.

[0151] At step **308**, the disc and substrate can be co-fired. That is, composite assembly **100** is fired. The co-firing temperature can be lower than the temperature at which disc was fired, to ensure that the physical and electrical properties of the disc remain unchanged. The co-firing temperature can be within the well-known range in which such components are conventionally fired. Importantly, co-firing causes the substrate to shrink around the disc, thereby securing them together. Afterwards, the outside surface of the composite assembly **100** can then be machined to ensure it is of a specified or otherwise predetermined OD. Further, this step can be used to metalize and/or magnetize the composite assembly **100** if the ferrite disc has not previously been magnetized.

[0152] Steps **310** and **312** show optional steps that can be taken after the co-firing of the composite assembly **100**. For example, additional components can be added **310** onto the substrate, such as circuitry, to form final electronic components. Further, in some embodiments the composite assembly **100** can be sliced **312**, or otherwise partitioned, to

form a number of discrete assemblies. In some embodiments, both these optional steps can be performed and the particular order is not limiting. In some embodiments, only one of the optional steps can be taken. In some embodiments, neither of the optional steps can be taken.

[0153] Accordingly, composite assemblies **100** can be used in manufacturing high frequency electronic components in the same manner as conventionally-produced assemblies of this type. However, the method of the present invention is more economical than conventional methods, as the invention does not involve the use of adhesives.

[0154] **Figure 24** illustrates an example embodiment of a circulator as discussed herein. Thick film silver can be printed as the circuit. As per standard circulator applications, the circulator includes Port 1, Port 2, and Port 3. One of these ports can be blocked off to form an isolator.

Telecommunication Base Station

[0155] Circuits and devices having one or more features as described herein can be implemented in RF applications such as a wireless base-station. Such a wireless base-station can include one or more antennas configured to facilitate transmission and/or reception of RF signals. Such antenna(s) can be coupled to circuits and devices having one or more circulators/isolators as described herein.

[0156] Thus, in some embodiments, the above-disclosed material can be incorporated into different components of a telecommunication base station, such as used for cellular networks and wireless communications. An example perspective view of a base station **2000** is shown in **Figure 25**, including both a cell tower **2002** and electronics building **2004**. The cell tower **2002** can include a number of antennas **2006**, typically facing different directions for optimizing service, which can be used to both receive and transmit cellular signals while the electronics building **2004** can hold electronic components such as filters, amplifiers, etc. discussed below. Both the antennas **2006** and electronic components can incorporate embodiments of the disclosed ceramic materials.

[0157] **Figure 25** shows a base station. The base station can include an antenna that is configured to facilitate transmission and/or reception of RF signals. Such signals can be generated by and/or processed by a transceiver. For transmission, the transceiver can

generate a transmit signal that is amplified by a power amplifier (PA) and filtered (Tx Filter) for transmission by the antenna. For reception, a signal received from the antenna can be filtered (Rx Filter) and amplified by a low-noise amplifier (LNA) before being passed on to the transceiver. In the example context of such Tx and Rx paths, circulators and/or isolators having one or more features as described herein can be implemented at or in connection with, for example, the PA circuit and the LNA circuit. The circulators and isolators can include embodiments of the material disclosed herein. Further, the antennas can include the materials disclosed herein, allowing them to work on higher frequency ranges.

[0158] **Figure 26** illustrates hardware **2010** that can be used in the electronics building **2004**, and can include the components discussed above with respect to **Figure 25**. For example, the hardware **2010** can be a base station subsystem (BSS), which can handle traffic and signaling for the mobile systems.

[0159] **Figure 27** illustrates a further detailing of the hardware **2010** discussed above. Specifically, **Figure 27** depicts a cavity filter/combiner **2020** which can be incorporated into the base station. The cavity filter **2020** can include, for example, bandpass filters such as those incorporating embodiments of the disclosed material, and can allow the output of two or more transmitters on different frequencies to be combined.

[0160] **Figure 28** illustrates a circuit board **30004** which can include an isolator/circulator/filter **3002** and can be incorporated into the base station discussed above.

[0161] From the foregoing description, it will be appreciated that inventive products and approaches for composite microstrip circulators/isolators, materials, and methods of production are disclosed. While several components, techniques and aspects have been described with a certain degree of particularity, it is manifest that many changes can be made in the specific designs, constructions and methodology herein above described without departing from the spirit and scope of this disclosure.

[0162] Certain features that are described in this disclosure in the context of separate implementations can also be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable subcombination. Moreover, although features may be described above as acting in

certain combinations, one or more features from a claimed combination can, in some cases, be excised from the combination, and the combination may be claimed as any subcombination or variation of any subcombination.

[0163] Moreover, while methods may be depicted in the drawings or described in the specification in a particular order, such methods need not be performed in the particular order shown or in sequential order, and that all methods need not be performed, to achieve desirable results. Other methods that are not depicted or described can be incorporated in the example methods and processes. For example, one or more additional methods can be performed before, after, simultaneously, or between any of the described methods. Further, the methods may be rearranged or reordered in other implementations. Also, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described components and systems can generally be integrated together in a single product or packaged into multiple products. Additionally, other implementations are within the scope of this disclosure.

[0164] Conditional language, such as “can,” “could,” “might,” or “may,” unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include or do not include, certain features, elements, and/or steps. Thus, such conditional language is not generally intended to imply that features, elements, and/or steps are in any way required for one or more embodiments.

[0165] Conjunctive language such as the phrase “at least one of X, Y, and Z,” unless specifically stated otherwise, is otherwise understood with the context as used in general to convey that an item, term, etc. may be either X, Y, or Z. Thus, such conjunctive language is not generally intended to imply that certain embodiments require the presence of at least one of X, at least one of Y, and at least one of Z.

[0166] Language of degree used herein, such as the terms “approximately,” “about,” “generally,” and “substantially” as used herein represent a value, amount, or characteristic close to the stated value, amount, or characteristic that still performs a desired function or achieves a desired result. For example, the terms “approximately”, “about”, “generally,” and “substantially” may refer to an amount that is within less than or equal to

10% of, within less than or equal to 5% of, within less than or equal to 1% of, within less than or equal to 0.1% of, and within less than or equal to 0.01% of the stated amount. If the stated amount is 0 (e.g., none, having no), the above recited ranges can be specific ranges, and not within a particular % of the value. For example, within less than or equal to 10 wt./vol. % of, within less than or equal to 5 wt./vol. % of, within less than or equal to 1 wt./vol. % of, within less than or equal to 0.1 wt./vol. % of, and within less than or equal to 0.01 wt./vol. % of the stated amount.

[0167] Some embodiments have been described in connection with the accompanying drawings. The figures are drawn to scale, but such scale should not be limiting, since dimensions and proportions other than what are shown are contemplated and are within the scope of the disclosed inventions. Distances, angles, etc. are merely illustrative and do not necessarily bear an exact relationship to actual dimensions and layout of the devices illustrated. Components can be added, removed, and/or rearranged. Further, the disclosure herein of any particular feature, aspect, method, property, characteristic, quality, attribute, element, or the like in connection with various embodiments can be used in all other embodiments set forth herein. Additionally, it will be recognized that any methods described herein may be practiced using any device suitable for performing the recited steps.

[0168] While a number of embodiments and variations thereof have been described in detail, other modifications and methods of using the same will be apparent to those of skill in the art. Accordingly, it should be understood that various applications, modifications, materials, and substitutions can be made of equivalents without departing from the unique and inventive disclosure herein or the scope of the claims.

WHAT IS CLAIMED IS:

1. A composite material for use as a radiofrequency component comprising:
a rod including a magnetic garnet material; and
a ring surrounding the rod, the ring being formed from a scheelite material having a firing temperature of 950 °C or below.
2. The composite material of claim 1 wherein the scheelite material has the chemical formula $\text{Li}_{0.05}\text{Bi}_{0.95}\text{Mo}_{0.1}\text{V}_{0.9}\text{O}_4$.
3. The composite material of claim 1 wherein the scheelite material has the chemical formula $\text{Bi}_{1-2x-z}\text{R}_z\text{M}'_x\text{V}_{1-x}\text{M}''_x\text{O}_4$, R being a rare earth element La, Ce, Pr, Sm, Nd, Gd, Dy, Tb, Ho, Er, Tm, Yb, Lu, Y or Sc, M' being Li, Na, or K, and M'' being Mo or W.
4. The composite material of claim 1 wherein the scheelite material has the chemical formula $(\text{Na},\text{Li})_{0.5x}\text{Bi}_{1-0.5x}(\text{Mo},\text{W})_x\text{V}_{1-x}\text{O}_4$, x being between 0 and 0.5.
5. The composite material of claim 1 wherein the scheelite material includes between 1 and 10 wt. % aluminum oxide.
6. The composite material of claim 5 wherein the scheelite material includes between 2 and 6 wt. % aluminum oxide.
7. The composite material of claim 1 wherein the scheelite material includes BiVO_4 .
8. The composite material of claim 1 wherein the scheelite material includes $(\text{Na}_{0.35}\text{Bi}_{0.65})(\text{Mo}_{0.7}\text{V}_{0.3})\text{O}_4$.
9. The composite material of claim 1 wherein the scheelite material includes $(\text{Na}_{0.2}\text{Bi}_{0.8})(\text{Mo}_{0.4}\text{V}_{0.6})\text{O}_4$.
10. A method of forming a composite material for use as an isolator or circulator in a radiofrequency device, the method comprising:
providing a rod including a magnetic garnet material;
providing an outer ring having a scheelite crystalline structure, the outer ring having a firing temperature of 950 °C or below;
entering the rod within an aperture in the outer ring; and

co-firing the outer ring and the rod together at a temperature of 950 °C or below to shrink the outer ring around an outer surface of the magnetic garnet material rod without the use of adhesive or glue and form a composite material.

11. The method of claim 10 wherein the outer ring has the chemical formula $\text{Li}_{0.05}\text{Bi}_{0.95}\text{Mo}_{0.1}\text{V}_{0.9}\text{O}_4$.

12. The method of claim 10 wherein the scheelite material has the chemical formula $\text{Bi}_{1-2x-z}\text{R}_z\text{M}'_x\text{V}_{1-x}\text{M}''_x\text{O}_4$, R being a rare earth element La, Ce, Pr, Sm, Nd, Gd, Dy, Tb, Ho, Er, Tm, Yb, Lu, Y or Sc, M' being Li, Na, or K, and M'' being Mo or W.

13. The method of claim 10 wherein the scheelite material has the chemical formula $(\text{Na,Li})_{0.5x}\text{Bi}_{1-0.5x}(\text{Mo,W})_x\text{V}_{1-x}\text{O}_4$, x being between 0 and 0.5.

14. The method of claim 10 wherein the scheelite material includes between 1 and 10 wt. % aluminum oxide.

15. The method of claim 14 wherein the scheelite material includes between 2 and 6 wt. % aluminum oxide.

16. The method of claim 10 wherein the magnetic garnet material rod includes Bi, Ca, Zr, Y, Fe, and O.

17. The method of claim 10 wherein the scheelite material includes BiVO_4 .

18. The method of claim 10 further including slicing the composite material.

19. A radiofrequency isolator or circulator comprising:

a rod including a magnetic garnet material; and

a ring surrounding the rod, the ring being formed from a scheelite material having a firing temperature of 950 °C or below.

20. The radiofrequency of claim 19 wherein the ring reduces in diameter around the magnetic garnet material rod during firing so that no adhesive is used to connect the ring with the magnetic garnet material rod.