

Sensor for Detecting Surface Defects in an Object and System Thereof

Cross-Reference to Related Application(s)

[0001] This application claims the benefit of Singapore Patent Application No. 10201802465S entitled "Near-Field Millimeter-Wave Leaky-Wave Antenna Beamforming System for Non-Destructive Testing (NDT)" and filed on 26 March 2018, which is expressly incorporated by reference herein in its entirety.

Technical Field

[0002] This disclosure generally relates to detection of surface defects in an object, for example, non-destructive detection of surface defects in an object, and more particularly to leaky-wave antenna and planar magic tee structures for realising non-destructive detection of surface defects in an object.

Background

[0003] Effective non-destructive detection of surface defects in an object such as a metal pipeline that is well insulated or protected requires removal of the insulation. Conventional non-destructive detection devices can employ X-ray machines. However, such devices are bulky and limit maneuverability while performing the defect detection, and X-rays poses health hazard when in operation. Other non-destructive detection techniques such as ultrasound, eddy current or shearography might offer smaller form factor devices. However, such techniques are unable to penetrate the insulation.

[0004] Millimetre-wave (mmwave) offers an alternative to the above for non-destructive detection of surface defects. At such high frequencies, beam steering based on phase shifting requires high frequency sweep or tuning in mmwave. This could be achieved using a leaky wave antenna with a substrate integrated waveguide (SIW) to offer scanning with relatively high gain. However, existing techniques are unable to provide a complete beam scanning that could provide a narrow beam to detect anomalies on or in the surface of the object.

Summary

[0005] According to a first aspect of the disclosure, a sensor for detecting surface defects in an object is provided. The sensor comprises:

- a leaky-wave antenna comprising an array of unit cells wherein each unit cell comprises:

- a slotted patch antenna overlaying a slotted substrate integrated waveguide (SIW);

a millimetre-wave transceiver; and

a circulator communicably coupled between the leaky-wave antenna and the millimetre-wave transceiver for controlling transmission and reception of millimetre-wave there between.

[0006] In some embodiments of the first aspect of the disclosure, the circulator comprises a planar magic tee which comprises an E-plane overlaying a H-plane, wherein the H-plane comprises:

a first SIW which comprises two collinear ports and a side port defining a T-junction, wherein each of the three ports comprises a microstrip-to-SIW transition, wherein the first SIW is formed with a first slot; and

a first via fence disposed along edges of the first SIW, which are outside the microstrip-SIW transitions of the three ports;

wherein the E-plane comprises:

a second SIW which comprises a single port comprising a microstrip-to-SIW transition, wherein a second slot is formed in the second SIW and disposed in fluid communication with the first slot; and

a second via fence disposed at locations of the second SIW, which are outside the microstrip-SIW transitions of the single port, wherein the second via fence defines an enclosure wall extending towards one of the collinear ports and two walls forming an open end directed towards the single port.

[0007] In some embodiments of the first aspect of the disclosure, the first slot is arranged along a line of symmetry between the collinear ports.

[0008] In some embodiments of the first aspect of the disclosure, the H-plane further comprises: a first tuning via disposed at the first SIW along a line of symmetry between the collinear ports.

[0009] In some embodiments of the first aspect of the disclosure, the first tuning via is located along the line of symmetry and closer to one of the edges which is most distal from the side port.

[0010] In some embodiments of the first aspect of the disclosure, the E-plane further comprises: a second tuning via disposed at the second SIW at a location which is between the two walls forming the open end and is closer to a shorter one of the two walls.

[0011] In some embodiments of the first aspect of the disclosure, the second tuning via is located closer to the shorter one of the two walls in a direction parallel to an axis through the collinear ports.

[0012] In some embodiments of the first aspect of the disclosure, the slotted SIW comprises:

- a lower dielectric layer interposed between two ground layers;
- a via fence traversing the lower dielectric layer and shorted to the two ground layers;

wherein the slotted patch antenna comprises:

- an upper dielectric layer; and
- a radiating patch disposed on a top side of the upper dielectric layer,

wherein an upper one of the two ground layers is juxtaposed against a bottom side of the upper dielectric layer.

[0013] In some embodiments of the first aspect of the disclosure, a height of the lower dielectric layer greater than a height of the upper dielectric layer, wherein the lower and the upper dielectric layer have the same relative permittivity and dielectric loss.

[0014] In some embodiments of the first aspect of the disclosure, the array of unit cells forms a single row parasitic slotted-patch array.

[0015] According to a second aspect of the disclosure, an apparatus for detection of surface defect in an object is provided. The apparatus comprises:

- the sensor of any one of the embodiments of the first aspect of the disclosure;
- a memory for storing instructions;
- a detector device for detecting millimetre-wave signals;
- a processor communicably coupled to the memory, detector device and the sensor and configured to execute the instructions to:
 - control transmission, from the millimetre-wave transceiver, of millimetre waves at different frequencies to produce a scanning beam for back-fire to end-fire scanning of a surface of an object;
 - receive, from the detector device, signals of the millimetre waves reflected off the surface of the object;
 - generate an image of the received signals of the reflected millimetre wave; and

determine presence of a defect from the generated image.

[0016] According to a third aspect of the disclosure, a method of fabricating a sensor device is provided. The method comprises:

communicably coupling a leaky-wave antenna to a planar magic tee; and

communicably coupling a millimetre-wave transceiver to the planar magic tee such that the planar magic tee is communicably coupled between the leaky-wave antenna and the millimetre-wave transceiver.

Brief Description of Drawings

[0017] Figure 1A shows a cross-sectional view of a unit cell of a leaky-wave antenna array as taken along line B-B;

[0018] Figure 1B shows a top view of the leaky-wave antenna array of Figure 1A;

[0019] Figure 1C shows a fabricated structure of the leaky-wave antenna device of Figure 1B;

[0020] Figure 2 illustrates a leaky-wave antenna scanning operation;

[0021] Figure 3 shows beam scanning angles and realized gain with frequency in relation to a leaky-wave antenna example;

[0022] Figures 4A to 4D illustrate radiation patterns produced by the leaky-wave antenna of Figure 3;

[0023] Figure 5A shows a perspective view of a planar magic tee;

[0024] Figure 5B shows a cross-sectional view of the planar magic tee of Figure 5A;

[0025] Figure 6 shows a top view of a H-plane of the magic tee of Figure 5A;

[0026] Figures 7A and 7B show top and bottom views of an E-plane of the magic tee of Figure 6;

[0027] Figure 8 illustrates return loss at four ports of a magic tee example;

[0028] Figure 9A illustrates a front view of propagation of electric field (E-field) in the magic tee example when power is fed into port 1;

[0029] Figure 9B illustrates a back view of Figure 9A;

[0030] Figure 10 illustrates a front view of propagation of electric field (E-field) in the magic tee example when power is fed into port 4;

[0031] Figure 11 illustrates magnitude of power division at port 2 and port 3 of the magic tee example in the operating frequency range;

[0032] Figure 12 illustrates isolation of power of the magic tee example in the operating frequency range;

[0033] Figure 13 illustrates amplitude imbalance between the in-phase and out-of-phase components of the magic tee example;

- [0034] Figure 14A shows the phases of S21 and S31 of the magic tee example;
- [0035] Figure 14B shows phase imbalance of S21 and S31 of Figure 14A;
- [0036] Figure 15A shows the phases of S24 and S34 of the magic tee example;
- [0037] Figure 15B shows phase imbalance of S24 and S34 of Figure 15A;
- [0038] Figure 16 shows a millimetre-wave system;
- [0039] Figure 17 shows a pipeline sample having three defects of different lengths and depths;
- [0040] Figure 18 shows an MMW image of the detected cracks in Figure 17;
- [0041] Figure 19 shows the pipeline sample of Figure 17, which is overlaid with an insulation;
- [0042] Figure 20A shows an MMW image of the pipeline having an insulation overlay of 2 mm thickness;
- [0043] Figure 20B shows an MMW image of the pipeline having an insulation overlay of 4 mm thickness; and
- [0044] Figure 21 shows a flowchart of a method of fabricating a sensor device; and
- [0045] Figure 22 is a flowchart of a method of fabricating a sensor device.

Detailed Description

[0046] In the following description, numerous specific details are set forth in order to provide a thorough understanding of various illustrative embodiments of the invention. It will be understood, however, to one skilled in the art, that embodiments of the invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure pertinent aspects of embodiments being described. In the drawings, like reference numerals refer to same or similar functionalities or features throughout the several views.

[0047] Embodiments described in the context of one of the methods or devices are analogously valid for the other methods or devices. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

[0048] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0049] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements. The terms “first”, “second” and “third”, etc. are used merely as labels, and are not intended to impose numerical requirements on their objects. The terms “comprising,” “including,” and “having” are intended to be open-ended and mean that there may be additional features or elements other than the listed ones. Identifiers such as “first”, “second” and “third” are used merely as labels, and are not intended to impose numerical requirements on their objects, nor construed in a manner imposing any relative position or time sequence between limitations. The term “and/or” includes any and all combinations of one or more of the associated listed items. Furthermore, terms such as “top”, “bottom”, “side”, “under”, “underneath”, “over”, “above” used herein are merely for ease of description and refer to the orientation of the features or elements as shown in the figures. It should be understood that any orientation of the features described herein is within the scope of the invention. Yet furthermore, the term “coupled” and related terms are used in an operational sense and are not necessarily limited to a direct physical connection or coupling. Thus, for example, two devices may be coupled directly, or via one or more intermediary devices. In certain examples, devices may be suitably coupled such that information or signal can be passed there between, while not sharing any physical connection with each other. For example, two devices may be communicably coupled via a wired or wireless connection. Based on the present disclosure, a person of ordinary skill in the art will appreciate a variety of ways in which coupling exists in accordance with the aforementioned definition.

[0050] According to one aspect of the disclosure, a sensor 100 for detecting surface defects in an object is provided. The sensor 100 comprises: a leaky wave antenna 10 comprising an array of unit cells wherein each unit cell comprises: a slotted patch antenna 14 overlaying a slotted substrate integrated waveguide (SIW) 16; a millimetre-wave transceiver for transmitting and receiving millimetre-wave such as through the SIW; and a circulator 20 communicably coupled between the leaky-wave antenna 10 and the millimetre-wave transceiver for controlling transmission and reception of millimetre-wave there between.

[0051] The SIW based leaky-wave antenna 10 may incorporate a meta-material to provide a scanning covering almost back-fire to end-fire directions with relatively high gain. A composite right/left-handed (CRLH) structure may be employed using a multi-layered SIW structure to provide an overlaying arrangement in which a slotted-patch antenna array is

disposed on top of a slotted SIW 16. This antenna configuration features LH/RH properties at different frequencies and therefore realizes beam scanning in both directions.

[0052] According to various embodiments, a SIW based leaky-wave antenna 10 is illustrated in Figures 1A to 1C. Figure 1C shows a fabricated structure of a leaky wave antenna device; Figure 1B shows a top view of a leaky-wave antenna device, e.g. a single row parasitic slotted-patch array, comprised in Figure 1C; and Figure 1A shows a cross-sectional view of a unit cell of the leaky-wave antenna array as taken along line B-B shown in Figure 1B.

[0053] In Figure 1A, the unit cell is illustrated in a z-z plane. Each unit cell comprises a lower dielectric layer 162, an upper dielectric layer 172, metal layers 164, 165, a radiating patch 142, and a feed line. The array or plurality of unit cells are integrated to form an antenna array.

[0054] The lower dielectric layer 162 is interposed between two grounded metal layers 164, 165 and therefore referred to as a lower ground layer 164 and an upper ground layer 165. A via fence 168 traverses the lower dielectric layer 162 and is electrically shorted to the two ground layers 164, 165. The via fence 168 may be provided by metal-filled vias or conductive posts disposed in via openings. A slot (not shown) may be provided in the centre of each unit cell of the SIW such that the lower dielectric layer 162, ground layers 164, 165 and via fence 168 form the slotted SIW 16.

[0055] The upper dielectric layer 172 is disposed or stacked on the slotted SIW 16. The upper dielectric layer 172 has a bottom side which is juxtaposed against the upper ground layer 165 of the lower dielectric layer 162 such that the upper ground layer 165 is interposed between the upper dielectric layer 172 and the lower dielectric layer 162. The upper dielectric layer 172 has a top side on which a radiating patch 142 is disposed or fabricated. The radiating patch 142 is connected to a feed line (not shown), e.g. microstrip feed line, to enable the radiating patch to be fed therefrom. To provide a parasitic slot, the radiating patch 142 may be provided with an opening 146, e.g. ring-slot, which may alternatively take on other shapes including but not limited to square, circular, square annular shape.

[0056] In Example 1 of leaky-wave antenna, a height of the lower dielectric layer 162 is greater than a height of the upper dielectric layer 172. The lower dielectric layer 162 may have height $h_1 = 0.254$ mm, relative permittivity $\epsilon_r = 3.0$, dielectric loss $\tan\delta = 0.001$; the

upper dielectric layer 172 may have height $h_2 = 0.127$ mm, relative permittivity $\epsilon_r = 3.0$, dielectric loss $\tan\delta = 0.001$. In this example, the relative permittivity and dielectric loss of both dielectric layers are the same. In some other examples, the relative permittivity and dielectric loss of both dielectric layers may be different.

[0057] In Example 2 of leaky-wave antenna which may incorporate parameters of either Example 1 or other examples, a CRLH multi-layered SIW based leaky-wave antenna is designed at 60 GHz-band and exhibits a wide range beam scanning with realized gain of more than 9.0 dBi.

[0058] Figure 2 illustrates a leaky-wave antenna scanning operation. A leaky-wave antenna operating in fundamental mode, is capable of continuous scanning from backfire ($\theta = -90^\circ$) to endfire ($\theta = +90^\circ$). Beam scanning depends on frequency (f) and scanning beam angle (θ) is a function of frequency. They can be expressed as $\theta(f) = \sin^{-1} \left[\frac{\beta(\omega)}{k_0} \right]$, where k_0 is the free space propagation constant with back-fire scanning, $\beta < k_0$ (left-handed region), end-fire scanning: $\beta > k_0$ (right-handed region), and bore-side scanning: $\beta = 0$ (balanced CRLH). At balanced condition (transition point), the series resonance and shunt resonance of both sides are equal ($L_R \times C_L = L_L \times C_R$).

[0059] Figure 3 shows beam scanning angles and realized gain with frequency in relation to a leaky-wave antenna of Example 2. Realized gain was more than 9.5 dBi over the 56 GHz to 70.0 GHz frequency range. Main radiation beam from antenna was produced with beam scanning angle from -66° to 50° across the frequency range 52 GHz to 70 GHz.

[0060] Figure 4A to 4D illustrate radiation patterns (in x-y plane) of a leaky-wave antenna of Example 2 at various frequencies of 57 GHz, 59 GHz, 63 GHz, and 64 GHz. The realised gains were 9.989 dB, 11.06 dB, 11.33 dB and 11.08 dB respectively. It can be observed from Figures 4A to 4D that dotted lines 400 define approximate areas representing realized gains of more than around 9.5 dB.

[0061] According to various embodiments, a circulator comprises a planar magic tee 20 which comprises an E-plane 24 overlaying or communicably coupled to an H-plane 22. Figures 5A, 5B, 6, 7A and 7B illustrate a planar magic tee 20 according to some embodiments.

[0062] Figure 5A shows a perspective view of a planar magic tee while Figure 5B shows a cross-sectional view thereof. The planar magic tee is a 4-port microwave component that enables in-phase as well as 180° out of phase power division. Similar to a conventional magic tee fabricated by combining rectangular waveguide sections together, the planar magic tee according to various embodiments of the invention comprises an E-plane overlaying a H-plane. In the H-plane, port 1, port 2 and port 3 form a T-junction of the H-plane. Port 1 is called the sum port (Σ). When power is fed into port 1, it is divided equally to ports 2 and 3. The outputs in port 2 and port 3 are in phase while port 4 is isolated, i.e. no power is transmitted through port 4. Port 4 is called the difference port (Δ). When power is fed into port 4, it is divided equally to port 2 and port 3 while port 1 is isolated. The outputs in port 2 and port 3 are out of phase by 180°. When power is fed into port 2 and port 3, the sum is obtained at port 1 and the difference is obtained at port 4. Figure 5B is a cross-sectional view of Figure 5A taken along a line traversing port 1 and port 4, wherein the bottom layer, i.e. H-plane, provides a ground plane for the magic tee.

[0063] Figure 6 shows a top view of a H-plane 22 which comprises a first SIW 220. The first SIW 220 comprises two collinear ports (see port 2 and port 3 in Figure 5A) and a side port (see port 1 in Figure 5A) such that these three ports or arms define a T-junction. At one end of each of the three ports or arms, a microstrip-to-SIW transition 222 is provided. The microstrip-to-SIW transitions convert Quasi-TEM mode existing in microstrip transmission line to the TE₁₀ mode (dominant mode with lowest cutoff frequency) in the waveguide (magic tee) with minimal loss. TE refers to transverse electric and indicates that the electric field is transverse to the direction of propagation. The ports are configured to electrically couple to other circuits and/or devices. The first SIW 220 is provided with a first via fence 228 disposed at locations which are outside the microstrip-SIW transitions 222 of the three ports. Such locations may be along edges of the first SIW 220 along each of the three ports. The first via fence 228 may be formed by a plurality of discontinuous or discrete walls, e.g. parallel rows of vias, but other non-parallel arrangements may be envisaged in other embodiments.

[0064] A first slot 226 may be provided or formed in the first SIW 220. The first slot 226 may be located along a line of symmetry between the collinear ports of the H-plane 22. The line of symmetry may be generally parallel to an axis of the side port and equidistant from free ends of collinear ports. The first slot 226 may be formed on a top layer, e.g. top metal layer, of the first SIW 220. As appreciated by persons skilled in the art, a SIW generally includes a dielectric layer interposed between a top metal layer and a bottom

metal layer. In one example, the first slot 226 may be an opening having a rectangular shape but may take on other suitable shapes in other embodiments.

[0065] In Example 1 of planar magic tee, a first slot 226 is located along a line of symmetry between the collinear ports of the H-plane 22 and formed in a top metal layer of the first SIW. The first slot 226 has a width of 0.2 mm and a length of 2.2 mm wherein the length is arranged along the line of symmetry.

[0066] In some embodiments, a first tuning via 224 may be provided and configured such that return loss at the desired frequency is high. In some examples, the first tuning via 224 may be located along the line of symmetry. In Example 1 of planar magic tee, the first tuning via 224 is located closer to, e.g. 1.055 mm from, one of the edges which is most distal from the side port of the H-plane 22.

[0067] Figures 7A and 7B show top and bottom views of an E-plane 24 which comprises a second SIW 240. The second SIW 240 comprises a single port (see port 4 in Figure 5A) which comprises a microstrip-to-SIW transition 242. The second SIW 240 is provided with a second via fence 248 disposed at locations of the second SIW 240, which are outside the microstrip-SIW transition 242 of the single port. The second via fence 248 comprise an enclosure wall 248a extending towards one of the collinear ports of the H-plane 22 and two walls 248b, 248c forming an open end directed towards the single port of the E-plane 24 (see Figure 5A). The enclosure wall 248a has two ends which are connected to the two walls 248b, 248c respectively. The two walls 248b, 248c may be parallel in certain embodiments. The enclosure wall 248a defines a spatial region for retaining wave propagation and its shape enables production of an electric field parallel to the E_{wall} . The enclosure wall 248a also includes a bend to provide an H-plane bend for isolating transmission between port 1 and port 4.

[0068] In some embodiments, a second slot 246 may be provided or formed in the second SIW 240 and disposed in fluid communication with the first slot 226 to realise the E-plane. Particularly, the second slot 246 may be formed in the bottom metal layer of the second SIW 240. The second slot 246 may have dimensions similar to or different from the first slot 226.

[0069] In some embodiments, a second tuning via 244 may be provided and configured such that the return loss at port 4 is high. The second tuning via 244 may be disposed at

the second SIW 240 at a location which is between the two walls 248b, 248c forming the open end of the second via fence 248 and is closer to a shorter one 248b of the two walls.

[0070] In Example 1 of planar magic tee, the second tuning via is located closer to the shorter wall 248b than to the longer wall 248c. Coordinates of the location of the second tuning via 244 may be defined by x_{tune} , e.g. 0.54 mm from the shorter one of the two walls in a direction parallel to an axis through the collinear ports, and y_{tune} , e.g. 0.41 mm from the shorter one of the two walls in a direction transverse to the axis of the collinear ports. Reference to the shorter one of the two walls may include a transition point between enclosure wall 248a and wall 248b.

[0071] In some embodiments, the second SIW comprises a second tuning via while the first SIW does not comprise a first tuning via. In other examples, the first SIW comprises a first tuning via while the second SIW does not comprise a second tuning via. In yet other examples, a tuning via may not be provided.

[0072] Table 1 lists structural parameters of a magic tee according to Example 1 of planar magic tee, which provide satisfactory results in the operating frequency range.

Table 1

Magic tee design parameters	Value for the 60 GHz design (mm)
Height of first / second SIW, h_{sub}	0.254
Distance from E_{wall} (x-direction) to tuning via, x_{tune}	0.54
Distance from via wall (in y-direction) to tuning via, y_{tune}	0.41
Distance from via wall to tuning via, h_{tune}	1.055
Length of slot, l_s	2.2
Width of slot, w_s	0.2
Width of E_{wall}	2.4
Length of first / second SIW, l_{siw}	7
Length of microstrip-to-SIW transition, $l_{\text{siw-ms}}$	2
Width of microstrip-to-SIW transition, $w_{\text{siw-ms}}$	1.41
Width of first / second SIW, W	2.7
Pitch between adjacent via holes, P	0.6
Diameter of via hole, D	0.254

[0073] Figure 8 illustrates return loss at four ports of the magic tee of Example 1. As shown by S-parameters, i.e. S₁₁ for port 1, S₂₂ for port 2, S₃₃ for port 3, and S₄₄ for port 4, satisfactory return loss was obtained at the ports over an operating bandwidth 58GHz to 61GHz.

[0074] Figure 9A illustrates propagation of electric field (E-field) in the planar magic tee of Example 1 when power was fed into port 1. Power fed into port 1 was divided equally into ports 2 and port 3. Port 4 was isolated and no power was transmitted through port 4. The outputs in port 2 and port 3 were in phase. Figure 9B illustrates a back view of Figure 9A.

[0075] Figure 10 illustrates propagation of electric field (E-field) in the planar magic tee of Example 1 when power was fed into port 4. Power fed into port 4 was also equally divided into port 2 and port 3. Port 1 was isolated and no power was transmitted through port 1. The outputs in port 2 and port 3 were out of phase by 180 degrees.

[0076] Figure 11 illustrates the magnitude of power division at port 2 and port 3 in the operating frequency range of Example 1 of planar magic tee. S₂₁ and S₃₁ correspond to S-parameters for port 2 and port 3 respectively when power was fed into port 1, and S₂₄ and S₃₄ correspond to S-parameters for port 2 and port 3 respectively when power was fed into port 4. It can be observed from Figure 11 that the insertion loss was minimal in the operating frequency range and therefore power division was equal or almost equal. The loss ranged from 0.6 dB to 1.1 dB in the frequency range 58 GHz to 61 GHz.

[0077] Figure 12 illustrates isolation of power in the operating frequency range of Example 1 of planar magic tee. S-parameter S₄₁ corresponds to isolation between port 4 and port 1, and S-parameter S₃₂ corresponds to port 3 and port 2. As shown, isolation between port 4 and port 1 was greater than 38 dB in the frequency range 58 GHz to 61 GHz; isolation between port 3 and port 2 was greater than 12 dB in the frequency range 58 GHz to 61 GHz.

[0078] Figure 13 illustrates amplitude imbalance between the in-phase and out-of-phase components. Amplitude imbalance (AI) in (dB) between S-parameters S₂₁ and S₃₁ and the amplitude imbalance between S-parameters S₂₄ and S₃₄ are illustrated in Figure 23. AI was less than 0.0375 dB in the frequency range 58 GHz to 61 GHz for the in-phase and out-of-phase components.

[0079] Figure 14A shows the phases of S21 and S31. It can be observed that the two components were in-phase and the phase imbalance (PI) between the two in-phase components was shown in Figure 14B. PI was less than 4.5° in the operating frequency range 58 GHz to 61 GHz.

[0080] Figure 15A shows the phases of S24 and S34. It can be observed that the two components were out-of-phase by 180° and the PI between two out-of-phase components was shown in Figure 15B. PI was less than 4.8° in the operating frequency range 58 GHz to 61 GHz.

[0081] Figures 8 to 15B were obtained from Example 1 of magic tee which was configured to operate at 60 GHz with an operating bandwidth ranging from 58 GHz to 61 GHz. Satisfactory return loss at all ports was obtained over the entire operating bandwidth, and the following observations may be made. In-phase and out-of-phase power division were achieved with very low loss ranging from 0.6 dB to 1.1 dB over the entire operating bandwidth. Isolation greater than 38 dB was obtained between port 1 and port 4. Isolation greater than 12 dB was obtained between port 2 and port 3. An amplitude imbalance of less than 0.0375 dB was obtained for both the in-phase components and the out-of-phase components. A phase imbalance of less than 4.8° was obtained for the in-phase and out-of-phase components.

[0082] Figure 16 shows a schematic diagram of a millimetre-wave system or apparatus which comprises: an automated three-dimensional X-Y-Z stage 80, a scanning probe 200 which may be mounted on the X-Y-Z stage 80, a data acquisition (DAQ) device 60, a processor 70 or computing device, e.g. personal computer, to control at least the motion of the X-Y-Z stage and the processing of the acquired data, a memory 72. Processor 70 is communicably coupled to at least the X-Y-Z stage 80, scanning probe 200, data acquisition device 60 and memory 72. It is to be appreciated that other communication coupling among components may not be shown.

[0083] In various embodiments, the X-Y-Z stage 80 provides a sample or object holder 82 for supporting a test sample 180 or object, e.g. pipeline. The X-Y-Z stage 80 may be operated by a servo motor which interfaces with a motion sensor control card or unit which is communicably coupled to the processor device 70 which in turn controls the X-Y-Z stage 80 to adjust its motion, e.g. x, y and/or z directions, to position the stage relative to the scanning probe 200 in a three-dimensional space. In some examples, the X-Y-Z stage 80

may have dimensions of approximately 1168 mm by 1098 mm by 450 mm and sensors may be installed to demarcate the boundary of the scanning area.

[0084] In some embodiments, the scanning probe 200 may include an oscillator 40, a single element millimetre-wave (MMW) module based non-destructive (NDT) sensor 100 and a detector device 50. The millimetre-wave module based sensor 100 may comprise a composite Right/Left Handed (CRLH) metamaterial based leaky-wave antenna 10, a magic tee 20, a millimetre-wave transceiver 30, an oscillator 40, a detector 50. It is to be appreciated that in some embodiments the oscillator 40 and/or detector 50 may be provided physically separate from the scanning probe 200.

[0085] The oscillator source 40 is configured to generate alternating current (AC) energy, e.g. millimetre waves, and is communicably coupled to the millimetre-wave transceiver 30 for transmitting wave energy thereto. The millimetre-wave transceiver 30 of the sensor 100 is configured to receive waves from the oscillator 40 and transmits the same to the circulator, e.g. magic tee 20 or other coupler. The millimetre-wave transceiver 20 is communicably coupled to the processor device 70 to enable the processor device 70 control transmission of millimetre waves from the millimetre-wave transceiver 30 at different frequencies so that the leaky-wave antenna 10 produces a scanning beam for back-fire to end-fire scanning of a surface of the test sample. The magic tee 20 is used as a power divider and directional coupler, and configured to receive millimetre waves from the millimetre-wave transceiver 30 and propagate or transmit the same to the leaky-wave antenna 10 of the sensor 100. The leaky-wave antenna 10 is configured to receive millimetre waves from the magic tee 20 and emit millimetre-wave signals, e.g. directed at test object 180. The detector device 50 is configured to receive to detect signals of millimetre waves reflected from test object 180 and transmit the same to the data acquisition device 60 which is communicably coupled to the detector device 50. The detector device 50 works in near field and scans the test object 180 using an x-y-z scanner.

[0086] In various embodiments, the data acquisition device 60 transmits the detected signals to the processor device 70. The processor 70 is configured to generate an image of the received signals of the reflected millimetre wave; and determine presence of a defect from the generated image.

[0087] In various embodiments, instructions are stored in the memory 72. The processor 70 is communicably coupled to the memory 72 to perform various control functions, e.g. control of X-Y-Z stage, motor, oscillator, millimetre-wave transceiver, data acquisition

device, and processing functions, e.g. processing of signals of the reflected millimetre wave, mapping, etc. In some examples, a visualiser program may be provided and stored in the memory, which interfaces with the motion sensor control card to control the X-Y-Z stage, and reads or acquires data from the data acquisition device, tabulates the acquired data and plots 2-dimensional diagrams in real-time.

[0088] Tests were carried out on metal pipeline samples having defects or cracks of different lengths and depths. The MMW NDT sensor was attached to the scanning probe, e.g. x-y-z scanner, and raster scanned to acquire an image of a pipe sample.

[0089] Figure 17 shows a partial close-up view of a pipeline sample 180 having three defects or cracks 181, 182, 183 of different lengths and depths. The pipeline 180 did not include a cover, e.g. insulation. Figure 18 shows an MMW image of pipeline 180 with three detected cracks 181, 182, 183. Areas surrounding the cracks are marked by boxes in dash-lines while the cracks are shown within the boxes as white (light) patches against black (dark) background.

[0090] Figure 19 shows the pipeline sample 180 of Figure 17, which is overlaid with an insulation 190, e.g. high density polyethylene (HDPE), having a thickness of 2 mm or 4 mm. Figure 20A shows an MMW image of pipeline 180 having an insulation overlay 190 of 2 mm thickness; Figure 20B shows an MMW image of pipeline 180 having an insulation overlay 190 of 4 mm thickness. In both Figures 20A and 20B, areas surrounding the detected cracks 181, 182, 183 are marked by boxes in dash-lines while the cracks are shown within the boxes as white (light) patches against black (dark) background.

[0091] It is to be appreciated from Figures 18, 20A and 20B that cracks on pipelines are detectable by the millimetre-wave system of the disclosure regardless whether the metal pipelines are insulated or non-insulated, for example, by high-density polyethylene (HDPE) insulation.

[0092] Figure 21 is a flowchart 210 of a method of fabricating a sensor device. In some embodiments, the sensor device fabricated by this method may be the above-described sensor device.

[0093] In block 2102, the method may include disposing a lower ground layer.

[0094] In block 2104, the method may include disposing a lower dielectric layer on or overlaying the lower ground layer.

[0095] In block 2106, the method may include disposing an upper ground layer on or overlaying the lower dielectric layer.

[0096] In block 2110, the method may include disposing an upper dielectric layer on or overlaying the upper ground layer.

[0097] In block 2112, the method may include disposing a radiating patch on or overlaying the upper dielectric layer.

[0098] In block 2114, the method may include forming or etching at least one opening in the radiating patch.

[0099] In block 2116, the method may include fabricating a first SIW which comprises two collinear ports and a side port defining a T-junction.

[0100] In block 2118, the method may include disposing a microstrip-to-SIW transition at each of the three ports.

[0101] In block 2120, the method may include forming or etching a first slot in the first SIW.

[0102] In block 2122, the method may include disposing a first via fence along edges of the first SIW, which are outside the microstrip-SIW transitions of the three ports.

[0103] In block 2124, the method may include fabricating a second SIW which comprises a single port.

[0104] In block 2126, the method may include disposing a microstrip-to-SIW transition at the single port.

[0105] In block 2128, the method may include forming or etching a second slot in the second SIW.

[0106] In block 2130, the method may include disposing a second via fence at locations of the second SIW, which are outside the microstrip-SIW transitions of the single port, wherein the second via fence defines an enclosure wall extending towards one of the collinear ports and two walls forming an open end directed towards the single port.

[0107] In block 2132, the method may include overlaying the second SIW on the first SIW such that the second slot is disposed in fluid communication with the first slot.

[0108] In block 2134, the method may include communicably coupling a leaky-wave antenna produced from blocks 2102 to 2114 to a planar magic tee produced from blocks 2116 to 2132.

[0109] In block 2136, the method may include communicably coupling a millimetre-wave transceiver to the planar magic tee such that the planar magic tee is communicably coupled between the leaky-wave antenna and the millimetre-wave transceiver.

[0110] It is to be appreciated that modifications to the above flow chart 2100 may be possible. For example, some of the above described method steps may be supplemented,

interchanged, combined and/or omitted. In certain examples, the method may further include, after block 2122, disposing a first tuning via at the first SIW along a line of symmetry between the collinear ports. In certain examples, the method may further include, after block 2132, disposing a second tuning via at the second SIW at a location which is between the two walls forming the open end and is closer to a shorter one of the two walls.

[0111] Figure 22 is a flowchart 2200 of a method of fabricating a sensor device. In some embodiments, the sensor device fabricated by this method may be the above-described sensor device.

[0112] In block 2202, the method may include fabricating a slotted leaky wave antenna. In some embodiments, fabricating a slotted leaky-wave antenna includes the steps described in blocks 2102 to 2114.

[0113] In block 2204, the method includes fabricating a slotted planar magic tee. In some embodiments, fabricating a slotted planar magic tee includes the steps described in blocks 2116 to 2132.

[0114] In block 2206, the method may include communicably coupling the leaky-wave antenna produced from 2202 to a planar magic tee produced from block 2204.

[0115] In block 2208, the method may include communicably coupling a millimetre-wave transceiver to the planar magic tee such that the planar magic tee is communicably coupled between the leaky-wave antenna and the millimetre-wave transceiver.

[0116] Embodiments of the disclosure provide advantages including but not limited to the following.

[0117] In various embodiments, a front end beam steering/phase array architecture in system-in-package (SiP) configuration is provided. The beam steering architecture is based on frequency sweep/tuning in the millimetre-wave. This is in contrast to the traditional phase shift methodology, which requires phase shifters to change the phase which in turn will result in beam steering. At higher frequencies, above 30 GHz, commercial phase shifters are not available. Therefore, frequency sweeping in the 60 GHz spectrum (57 GHz to 64 GHz) is used in the illustrated embodiments.

[0118] Conventional uniform leaky-wave antennas emit radiation in the forward direction only. However, periodic type leaky-wave antenna can produce backward radiation, and its broadside radiation is restricted by the stop band between the forward and backward region. A composite right/left-handed transmission line (meta-material) based leaky-wave

antennas, in accordance of various embodiments of the disclosure, improve broadside gain when balanced condition is satisfied, thus offering a scan coverage of almost back-fire to end-fire directions with relatively high gain.

[0119] Conventional magic tee structure is bulky, has narrow band performance and cannot be integrated easily with other planar microwave components. Substrate Integrated Waveguide (SIW) based microwave components provide an attractive alternative to conventional waveguide structures, yet retaining their advantageous properties such as high Q (quality factor) and low loss while being less bulky and more easily integrated with other planar microwave components.

[0120] Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the disclosure. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the disclosed embodiments. The embodiments and features described above should be considered exemplary.