

Package and a system for cooling a radio-frequency (RF) circuitTechnical Field

The present disclosure relates to a package and a system for cooling a radio-frequency (RF) circuit.

5 Background

Thermal management of RF circuits, particularly for high-power RF circuits such as power amplifiers, is important to maintain high performances of the RF circuits. A main RF performance limiting factor relates to the providence of an appropriate thermal solution, which requires the thermal solution to have a low thermal resistance for
10 transferring unwanted heat away from the RF circuits without affecting the RF circuit or its performances. Meeting this requirement becomes increasingly challenging when a RF signal combining design is employed and/or miniaturisation of the RF device is required.

High-power RF circuits are typically achieved by integrating multiple power amplifier
15 chips and combining their powers. One way of combining multiple power amplifier chips or circuits is by spatially combining them in a waveguide. Heat is then conducted away from these power amplifier chips via the substrate towards the waveguide. In this case, the thermal performance is limited by the thermal interface material (TIM) between the power amplifier chips and the substrate, and between the substrate and
20 the waveguide. The thermal conductivity of the substrate also plays an important role for heat transfer in this case. In addition, this conventional thermal solution is typically bulky and introduces difficulties for integrating this solution directly on RF circuits without compromising their RF performances. Further, this introduces complexity to the design of the power circuits as considerations have to be taken in relation to thermal
25 interfaces between the power circuits and the substrate and between the substrate and the waveguide. This also adds complexity to the fabrication processes required for introducing this thermal solution to the high-power RF circuits.

Another thermal solution for RF circuits is by direct liquid cooling using convection and conduction strategies. In direct liquid cooling, a RF circuit or a RF chip is immersed in a
30 liquid coolant. As an example, a microwave monolithic integrated circuit (MMIC) can be sealed with a liquid coolant inside a package for direct cooling. This direct cooling

method is generally effective, but has short-comings in relation to liquid interconnection effects and an interaction between the liquid and the MMIC which can be detrimental to the RF performance of the MMIC.

- 5 It is therefore desirable to provide a package and a system for cooling a radio-frequency (RF) circuit which address the aforementioned problems and/or provides a useful alternative. Further, other desirable features and characteristics will become apparent from the subsequent detailed description and the appended claims, taken in conjunction with the accompanying drawings and this background of the disclosure.

Summary

- 10 Aspects of the present application relate to a package and a system for cooling a radio-frequency (RF) circuit.

In accordance with a first aspect, there is provided a package for cooling a radio-frequency (RF) circuit, the package comprising: a hollow waveguide having a first end, a second end, and a sidewall connecting the first end and the second end to form an enclosure for the RF circuit, the first end being opposite to the second end, wherein the hollow-waveguide has through-holes formed on one or more portions of the sidewall, the through-holes being adapted to allow a liquid coolant to flow through the hollow waveguide for cooling the RF circuit, and wherein, in use, the hollow waveguide is completely filled with the liquid coolant, and is adapted to propagate a RF signal from the first end to the second end of the hollow waveguide.

- 20 By having a hollow waveguide forming an enclosure for a RF circuit and having through-holes being adapted to allow a liquid coolant to flow through the hollow waveguide, direct cooling of the RF circuit is provided. The package is adapted to allow the liquid coolant to circulate and flow across the RF circuit or chip without affecting the RF performance, thereby improving cooling efficiency. Particularly, where the package is in use, the hollow waveguide is completely filled with the liquid coolant and is adapted to propagate a RF signal from the first end to the second end of the hollow waveguide. This ensures that the RF performance of the RF circuit will not be affected as a dielectric inside the hollow waveguide, that being the liquid coolant when the hollow waveguide is completely filled, is homogeneous. The RF signal can then propagate along the hollow waveguide, while the liquid coolant flows through the hollow waveguide to cool the RF circuit without affecting its RF performance.

The through-holes may include two arrays of through-holes formed on opposite portions of the sidewall.

The opposite portions of the sidewall may be uniformly populated with the two arrays of through-holes, and a diameter and a shape of each of the through-holes and a pitch
5 between adjacent through-holes of the two arrays of through-holes may be identical.

The diameter and the pitch may be less than 0.1 of an operating wavelength of the RF circuit.

The package may comprise a dielectric film adapted to seal each of the first end and the second end of the hollow waveguide.

10 The dielectric film may include a microwave material having a dielectric constant (Dk) of 2.1 and a low loss tangent (Df) of 0.001 and a thickness of 0.5 mm.

The package may comprise an electrically conductive frame coupled to each of the first end and the second end of the hollow waveguide, the electrically conductive frame may have an opening with an area larger than a planar area of the dielectric film and may
15 be adapted to be centred with a centre of the dielectric film.

The package may comprise a thermal pipe adapted to enclose the hollow waveguide and is in fluid connection with the hollow waveguide, the thermal pipe may have a liquid circulation inlet for receiving the liquid coolant to be provided to the hollow waveguide and a liquid circulation outlet for returning the liquid coolant from the hollow waveguide,
20 the liquid circulation inlet and the liquid circulation outlet may be adapted to allow circulation of the liquid coolant through the hollow waveguide for cooling the RF circuit.

The liquid circulation inlet may include one or more inlet holes and the liquid circulation outlet may include one or more outlet holes, at least one of the one or more inlet holes and the one or more outlet holes may be aligned to the through-holes formed on the
25 one or more portions of the sidewall of the hollow waveguide.

The thermal pipe may be isolated electrically from the hollow waveguide.

The package may comprise the RF circuit, the RF circuit may be positioned within the hollow waveguide to enable the liquid coolant flowing through the hollow waveguide to be in a direction substantially in plane to a longitudinal plane of the RF circuit.

The package may comprise a RF combiner input and a RF combiner output operationally connected to the RF circuit, each of the RF combiner input and the RF combiner output may comprise a RF combiner circuit having multiple tapered slots to couple the RF signal from the hollow waveguide to a two-dimensional (2D) planar transmission line.

The RF circuit may be integrated on a RF circuit board in bare die using either flip-chip or wire bonding.

The package may comprise one or more additional RF circuits integrated on the RF circuit board.

10 The package may comprise one or more additional RF circuit board, each of the one or more additional RF circuit board may have one or more further RF circuits.

A cross-section of the hollow waveguide may include one of: a circular cross-section, a square cross-section, a rectangular cross-section, a hexagonal cross-section and an octagonal cross-section.

15 In accordance with a second aspect, there is provided a package for cooling a radio-frequency (RF) circuit, the package comprising: a hollow waveguide having a first end, a second end, and a sidewall connecting the first end and the second end to form an enclosure for the RF circuit, the first end being opposite to the second end, and the first end and the second end of the hollow waveguide are each sealed using a dielectric film,
20 wherein two arrays of through-holes are formed on opposite portions of the sidewall of the hollow waveguide, the through-holes being adapted to allow a liquid coolant to flow through the hollow waveguide for cooling the RF circuit; and a thermal pipe adapted to enclose the hollow waveguide and is in fluid connection with the hollow waveguide, wherein a cross-section of the thermal pipe is larger than a cross-section of the hollow
25 waveguide and having a centre being approximately centred with a centre of the cross section of the hollow waveguide, the thermal pipe having a liquid circulation inlet for receiving the liquid coolant to be provided to the hollow waveguide and a liquid circulation outlet for returning the liquid coolant from the hollow waveguide, the liquid circulation inlet and the liquid circulation outlet being adapted to allow circulation of the
30 liquid coolant through the hollow waveguide for cooling the RF circuit, the thermal pipe being isolated electrically from the hollow waveguide, wherein, in use, the hollow

waveguide is completely filled with the liquid coolant, and is adapted to propagate a RF signal from the first end to the second end of the hollow waveguide.

In accordance with a third aspect, there is provided a system for cooling a radio-frequency (RF) circuit, the system comprising: any preceding package; a liquid coolant reservoir configured to provide the liquid coolant to the package for cooling the RF circuit and to receive the liquid coolant from the package; a pump configured to drive the liquid coolant from the liquid coolant reservoir to the package; and a radiator configured to cool the liquid coolant received from the liquid coolant reservoir prior to the liquid coolant being provided to the package.

10 The liquid coolant may be circulated at a flow rate of 10 L/min. The liquid coolant may have a dielectric constant of 1.9 measured at 1 kHz and an electrical resistivity of 4.0×10^{15} Ohm•cm.

It should be appreciated that features relating to one aspect may be applicable to the other aspects. Embodiments of a package and a system for cooling a RF circuit comprises a hollow waveguide forming an enclosure for a RF circuit and having through-holes being adapted to allow a liquid coolant to flow through the hollow waveguide to provide direct cooling of the RF circuit. The package is adapted to allow the liquid coolant to circulate and flow across the RF circuit or chip without affecting the RF performance, thereby improving cooling efficiency. Particularly, where the package is in use, the hollow waveguide is completely filled with the liquid coolant and is adapted to propagate a RF signal from the first end to the second end of the hollow waveguide. This ensures that the RF performance of the RF circuit will not be affected as a dielectric inside the hollow waveguide, that being the liquid coolant when the hollow waveguide is completely filled, is homogeneous. The RF signal can then propagate along the hollow waveguide, while the liquid coolant flows through the hollow waveguide to cool the RF circuit without affecting the RF performance.

Brief description of the drawings

Embodiments will now be described, by way of example only, with reference to the following drawings, in which:

30 Figure 1 shows a schematic of longitudinal section of a package for cooling a radio-frequency (RF) circuit in accordance with an embodiment;

Figure 2 shows a schematic of a perspective view of a cross-section of a portion of the package of Figure 1 in accordance with an embodiment;

Figure 3 shows a schematic of a top-down perspective view of the package of Figure 1 to illustrate the detachable waveguides at each end of the hollow waveguide of the package in accordance with an embodiment;

Figure 4 shows a schematic of a top-down perspective view of the package of Figure 1 with waveguides attached at each end of the hollow waveguide of the package in accordance with an embodiment;

Figure 5 shows a schematic of a longitudinal section of a hollow waveguide of the package of Figure 1 in accordance with an embodiment;

Figure 6 shows a schematic of a cross-sectional view of an end of the hollow waveguide of Figure 5 in accordance with an embodiment;

Figure 7 shows schematics of a top view and a longitudinal section of the hollow waveguide of Figure 5 to illustrate arrangement of the through-holes formed on the sidewall of the hollow waveguide in accordance with an embodiment;

Figure 8 shows schematics of a top view and a longitudinal section of a thermal pipe of a package for cooling a radio-frequency (RF) circuit in accordance with an embodiment;

Figure 9 shows a schematic of a longitudinal section of a package to illustrate a liquid level of a liquid coolant for cooling a radio-frequency (RF) circuit in accordance with an embodiment;

Figure 10 shows a schematic of a system for cooling a radio-frequency (RF) circuit in accordance with an embodiment;

Figure 11 shows a schematic of a three-dimensional (3D) model of the package used for 3D electromagnetic (EM) simulation in accordance with an embodiment;

Figure 12 shows a graph of simulated S-parameters for the back-to-back liquid coolant filled hollow waveguide using the 3D model of Figure 11 in accordance with an embodiment;

Figure 13 shows a simulated three-dimensional (3D) thermal contour plot of RF circuits by direct cooling using a package in accordance with an embodiment; and

Figure 14 shows a schematic of a RF circuit being integrated on a RF circuit board in a bare die using a flip-chip arrangement in accordance with an embodiment.

5 Detailed description

Exemplary embodiments relate to a package and a system for cooling a radio-frequency (RF) circuit.

It is appreciated that in the present application, the use of the singular includes the plural unless specifically stated otherwise. It should be noted that, as used in the
10 specification and the appended claims, the singular forms “a”, “an” and “the” include plural referents unless the context clearly dictates otherwise. Further, the use of the term “including”, “comprising”, and “having” as well as other forms, such as “include”, “comprise”, “have” are not considered limiting.

As used herein, the term “and/or” includes any and all combinations of one or more of
15 the associated listed items.

The present disclosure describes embodiments of a package and a system for cooling a RF circuit by direct liquid cooling. In these embodiments, a hollow three-dimensional (3D) waveguide is provided where the RF circuit is integrated inside or enclosed within the hollow waveguide. The hollow waveguide is designed to have through-holes
20 formed on one or more portions of its sidewall, the through-holes being adapted to allow a liquid coolant to flow through the hollow waveguide for cooling the RF circuit. In use, the hollow waveguide is completely filled with the liquid coolant, and is adapted to propagate a RF signal from the first end to the second end of the hollow waveguide. In an embodiment, the hollow waveguide is further provided within a thermal pipe and a
25 liquid level inside the thermal pipe is always above the through-holes of the hollow waveguide so that a dielectric inside the hollow waveguide is filled with the liquid coolant to provide a homogenous medium for transmission of the RF signal within the hollow waveguide. In this way, the RF performance of the RF circuit is not affected.

Figure 1 shows a schematic of longitudinal section of a package 100 for cooling a
30 radio-frequency (RF) circuit in accordance with an embodiment.

The package 100 includes a hollow waveguide 102 having a first end 104, a second end 106, and a sidewall 108 connecting the first end 104 and the second end 106 to form an enclosure for a RF circuit 110. In the present embodiment, the hollow waveguide has a rectangular shape and an array of through-holes 112 is formed on each of a top longitudinal portion and a bottom longitudinal portion of the sidewall 108 of the hollow waveguide 102. The top longitudinal portion is opposite to the bottom longitudinal portion as shown in Figure 1. These arrays of through-holes are adapted to allow a liquid coolant to flow through the hollow waveguide 102 for cooling the RF circuit 110. This hollow waveguide 102 is adapted to enclose the RF circuit 110 and to support radio frequency (RF) and/or electromagnetic (EM) wave propagation in a lateral or longitudinal direction e.g. from the first end 104 to the second end 106 of the hollow waveguide 102 as shown in Figure 1. In the present embodiment, integrated RF connection provided by integrating the RF circuit 110 within the hollow waveguide 102 reduces RF loss for high frequency and high-power applications.

Also shown in Figure 1 is that the first end 104 (e.g. an input) and the second end 106 (e.g. an output) of the hollow waveguide 102 are connected directly to standard waveguides 114, 116 respectively. In the present embodiment, the RF circuit 110 (e.g. a high-power RF amplifier) can be integrated onto a RF circuit board 111. The RF circuit board 111 may comprise an input RF combiner and an output RF combiner. In the present embodiment, internal dimensions of the rectangular hollow waveguide 102, i.e. a width and a height of a cross-section of the hollow waveguide 102, are optimised to fit a width of the RF circuit board 111 for integrating with the RF circuit/ RF chip and RF input/output power combiners. To enhance thermal and RF performances using this package 100, the RF circuit 110 is integrated directly on the RF circuit board 111 in bare die using either using a flip-chip or wire bonding connection in the present embodiment. The RF input/output power combiners are each formed using a multiple tapered slot design to couple or form the RF signal from the rectangular hollow waveguide 102 to a two-dimensional (2D) planar transmission line. In the present embodiment, the multiple tapered slot design includes a Vivaldi tapered line profile which has a slot width that increases exponentially. It should be appreciated that other tapered line profiles such as Raise Cosine, Antipodal Fermi or linear, etc. can be used. Depending on the requirements of the RF application, more than one RF circuit boards

can be formed or provided inside the hollow waveguide 102. Further, it should be appreciated that each RF circuit board can include one or more RF circuits or RF chips.

Further, in the present embodiment, the package comprises a thermal pipe 118 adapted to enclose the hollow waveguide 102. The thermal pipe 118 is in fluid connection with the hollow waveguide 102. The thermal pipe 118 has a liquid circulation inlet 120 for receiving the liquid coolant to be provided to the hollow waveguide 102, and a liquid circulation outlet 122 for returning the liquid coolant from the hollow waveguide 102. The liquid circulation inlet 120 and the liquid circulation outlet 122 are adapted to allow circulation of the liquid coolant through the hollow waveguide 102 for cooling the RF circuit 110. As shown in Figure 1, the hollow waveguide 102 is provided within the thermal pipe 118 which allows the liquid coolant to flow vertically through the hollow waveguide 102 (i.e. from a top side to a bottom side of the hollow waveguide 102). In the present embodiment, RF or EM waves propagate laterally along the hollow waveguide 102 from the first end 104 to the second end 106. Each liquid circulation inlet 120 and liquid circulation outlet 122 may include one or more liquid inlets and liquid outlets respectively. In the present embodiment as shown in Figure 1, there are three liquid inlets for the liquid circulation inlet 120 and three liquid outlets for the liquid circulation outlet 122, but it should be appreciated that the number of liquid inlets and/or liquid outlets of the thermal pipe 118 can vary. Also shown in Figure 1 is that the liquid circulation inlet 120 and the liquid circulation outlet 122 are formed on the top side and the bottom side of the hollow waveguide 102 respectively so that the liquid circulation inlet 120 and liquid circulation outlet 122 are positioned at the same sides of the through holes formed on the side wall 108 of the hollow waveguide 102 for ease of liquid coolant circulation. The package 100 comprising the hollow waveguide 102 and the thermal pipe 118 are operationally connected to a system used for circulating the liquid coolant through the hollow waveguide 102. This is shown and described in relation to Figure 10.

As exemplified in Figure 1, in the present embodiment, the liquid circulation inlet 120, the liquid circulation outlet 122 and the through-holes formed on the sidewall 108 of the hollow waveguide 102 are adapted to enable the liquid coolant to pass through from one side of the hollow waveguide to the opposite side of the hollow waveguide directly without affecting EM wave propagation and an operation of the RF circuit 110 inside the hollow waveguide 102. Further, positions of the through holes at the top side and

the bottom side of the hollow waveguide 102 are aligned so that the liquid coolant can pass through the hollow waveguide directly with the least impedance. In the present embodiment, the RF circuit 110 or the RF circuit board 111 inside the hollow waveguide 102 is placed vertically (i.e. having a planar surface perpendicular to the top side surface or the bottom side surface of the hollow waveguide 102) such that the planar surface of the RF circuit 110 or RF circuit board is parallel to the flow of the liquid coolant. Further, the RF circuit 110 provided inside the hollow waveguide 102 is placed so that a planar area of the RF circuit 110 is along a longitudinal plane of the hollow waveguide 102. In other words, a longitudinal direction of the RF circuit 110 is parallel with respect to portions of the sidewall 108 having the through-holes. In the present embodiment, the liquid circulation inlet 120 and the liquid circulation outlet 122, which interface with the external liquid coolant circulation circuit (see e.g. the system in relation to Figure 10), are provided at the thermal pipe 118 to minimise interference to the RF transmission and RF circuit performance inside the hollow waveguide 102. In this way, the hollow waveguide 102 can be adapted independently to optimise transmission of the RF/EM waves within the hollow waveguide 102, while the thermal pipe 118 can be configured independently for controlling and optimising cooling of the RF circuit 110 by controlling a flow of the liquid coolant through the hollow waveguide 102. In the present embodiment, the hollow waveguide 102 also forms a RF shield to prevent an external structure from affecting the internal RF circuit 110. In the present embodiment, the thermal pipe 118 is also configured to be isolated electrically from the hollow waveguide 102.

In the present embodiment, both lateral ends (i.e. the first end 104 and the second end 106) of the hollow waveguide 102 are sealed using a dielectric material 124 (e.g. a dielectric film / sheet) coupled with a conductive frame (e.g. a metal frame) extending beyond the opening of the hollow waveguide 102. These features are more clearly shown in relation to Figures 5 and 6 below. In this way, the liquid coolant is contained within the hollow waveguide 102 but RF or EM signals can still propagate through the hollow waveguide 102. Dimensions of the opening of the conductive frame can be optimised to minimise impedance discontinuity between the hollow waveguide and the standard waveguides 114, 116 caused by the dielectric material 124.

Figure 2 shows a schematic of a perspective view 200 of a cross-section of a portion of the package 100 of Figure 1 in accordance with an embodiment.

In the present embodiment, two RF circuit boards 202, 204 were employed with each of the RF circuit boards 202, 204 comprising two RF circuits / RF chips 206. Hence, the RF amplification of the present embodiment is four times (4x) of the RF amplifier gain.

Also shown in Figure 2 is that these two RF circuit boards 202, 204 were enclosed
5 within the rectangular hollow waveguide 102 which in turn was enclosed within the thermal pipe 118 of the package 100. In this perspective view 200, it can be shown that the through-holes formed on the sidewall 108 of the hollow waveguide 102 includes two arrays 208, 210 of through-holes formed on opposite portions of the sidewall 108. In the present embodiment, the opposite portions of the sidewall are the top portion
10 and the bottom portion of the sidewall 108, and these opposite portions are uniformly populated with the two arrays 208, 210 of through-holes, where a diameter, a pitch and a shape of the through-holes are identical.

Figure 3 shows a schematic of a top-down perspective view 300 of the package 100 of Figure 1 in accordance with an embodiment.

15 As shown in Figure 3, detachable waveguides 302, 304 can be attached to each ends of the rectangular hollow waveguide 102. Also shown in Figure 3 is that each ends of the hollow waveguide 102 are sealed with a dielectric film 306. For optimal performance, the dielectric film 306 is designed using a low loss tangent (Df) and low dielectric constant (Dk) material and the thickness of the dielectric film 306 is adapted
20 to be as thin as possible to reduce RF loss. In the present embodiment, the dielectric film 306 includes a microwave material with a Dk of 2.1 and Df of 0.001 and a thickness of 0.5 mm. An orientation of the package 100 is shown using the Cartesian axes 308 x, y and z of Figure 3. To be clear, the longitudinal axis of the hollow waveguide 102 is the y-axis while the x-z plane defines the cross-section of the hollow
25 waveguide 102. Though not shown in Figure 3, the circuit boards 202, 204 are placed in plane to the y-z plane in this orientation.

Figure 4 shows a schematic of a top-down perspective view 400 of the package 100 of Figure 1 in accordance with an embodiment, with the waveguides 302, 304 being attached at each end of the hollow waveguide 102 of the package 100.

30 Figure 5 shows a schematic of a longitudinal section 500 of the hollow waveguide 102 of the package 100 of Figure 1 in accordance with an embodiment. Figure 5, together

with Figure 6, provides illustrations of the dielectric films and the electrically conductive frames formed at the ends 104, 106 of the hollow waveguide 102.

As shown in Figure 5, dielectric films 502, 504 are adapted to seal the first end 104 and the second end 106 of the hollow waveguide 102, respectively. Also shown in Figure 5 is that electrically conductive frames 506, 508 are coupled to the first end 104 and the second end 106 of the hollow waveguide, where the electrically conductive frames each has an opening with an area larger than a planar area of the dielectric films 502, 504. In an embodiment, the dielectric films 502, 504 and the electrically conductive frames 506, 508 are integrated at both ends of the hollow waveguide 102. The longitudinal section 500 also shows an array of through-holes 510 formed on a top side of the hollow waveguide 102 and an array of through-holes 512 formed on a bottom side of the hollow waveguide 102. In the present embodiment, the array of through-holes 510 and the array of through-holes 512 formed have identical size, pitch and shape, and these arrays of through-holes 510 and 512 are aligned with one another so as to ease the flow of liquid coolant through the hollow waveguide 102.

Figure 6 shows a schematic of a cross-sectional view 600 of an end of the hollow waveguide 102 of Figure 5 in accordance with an embodiment.

A dielectric film 602 placed within the opening of an electrically conductive frame 604 at one end of the hollow waveguide 102 is shown. As shown in Figure 6, the electrically conductive frame 604 is adapted to be centred with a centre of the dielectric film 602. In other words, the dielectric film 602 is centred within an opening of the electrically conductive frame 604.

To minimise an impedance discontinuity between the hollow waveguide 102 and the standard waveguides 114, 116, 302, 304, internal opening dimensions of the electrically conductive frame 604 (e.g. a metal frame) are optimised together with a thickness of the dielectric film 602. An internal height 608 and an internal width 610 of the hollow waveguide 102 are co-designed with the RF combiner and coupler of the RF circuit board. The dielectric film 602 is also designed with the electrically conductive frame 604 having the opening with an opening width 612 and an opening height 614 to reduce the impedance mismatch between the liquid-filled hollow waveguide 102 and a standard waveguide at each of the ends of the hollow waveguide 102. Dimensions of the opening of the electrically conductive frame 604 are optimised to minimise the

impedance discontinuity caused by the dielectric film. Impedance matching in the present embodiment is optimised to achieve a maximum power transfer (e.g. return loss less than $\sim$ -15dB) and to avoid resonance in the present embodiment.

Figure 7 shows schematics of a top view 700 and a longitudinal section 710 of the hollow waveguide 102 of Figure 5 to illustrate arrangement of the through-holes formed on the sidewall 108 of the hollow waveguide 102 in accordance with an embodiment.

As shown in Figure 5, an array of through-holes 510 is formed on the top side of the hollow waveguide 102 and an array of through-holes 512 is formed on the bottom side of the hollow waveguide 102. A diameter 702 of each of the through-holes and a pitch 704 between adjacent through-holes are designed or optimised such that an operation of the RF circuit / RF chip and power-combining circuits are not affected. In the present embodiment, this is achieved by ensuring that their dimensions are much smaller than the shortest RF / EM signal wavelength (i.e. the highest operating frequency). In the present embodiment, the diameter 702 and the pitch 704 are less than 0.1 of an operating wavelength of the RF circuit.

In the present embodiment, the diameter 702 of each of the through-holes or a hole size is designed to be big enough such that the liquid coolant can flow through the hollow waveguide 102 smoothly. The effect of the holes on the RF performance can be simulated and optimised using a three-dimensional (3D) electro-magnetic (EM) simulator, which is described in relation to Figure 11 below.

Figure 8 shows schematics of a top view 800 and a longitudinal section 810 of the thermal pipe 118 of the package 100 of Figure 1 for cooling a radio-frequency (RF) circuit in accordance with an embodiment.

The liquid circulation inlet 120 of the thermal pipe 118 for receiving the liquid coolant to be provided to the hollow waveguide 102 and the liquid circulation outlet 122 of the thermal pipe 118 for returning the liquid coolant from the hollow waveguide 102 are shown in Figure 8. In the present embodiment, the liquid circulation inlet 120 is provided at a top side of the hollow waveguide 102 and the liquid circulation outlet 122 is provided at a bottom side of the hollow waveguide 102 so that these are aligned with the through-holes of the hollow waveguide 102 to allow the liquid coolant to flow easily or smoothly through the through-holes into the hollow waveguide 102 to cool the RF

circuit 110 within the hollow waveguide 102 and to exit at the opposite side (i.e. the bottom side) of the hollow waveguide 102. As the thermal pipe 118 is isolated electrically by the hollow waveguide 102, the hollow waveguide 102 acts as an electrical shield, and the liquid circulation inlet 120 and the liquid circulation outlet 122 can be independently designed to maximise thermal performance provided by the package 100 without affecting the RF performance of the RF circuit. It is also noted that the liquid coolant inside the hollow waveguide 102 is prevented from flowing out of the RF connections at both ends of the hollow waveguide 102 by the dielectric seals 502, 504.

- 10 Figure 9 shows a schematic of a longitudinal section 900 of the package 100 to illustrate a liquid level of a liquid coolant for cooling a radio-frequency (RF) circuit in accordance with an embodiment.

As shown in Figure 9, the thermal pipe 118 forms an enclosure or a tank for the liquid coolant with the hollow waveguide 102 being formed within the thermal pipe 118. In the present embodiment, the thermal pipe 118 is adapted to surround the entire hollow waveguide 102 internally. The liquid circulation inlet 120 and the liquid circulation outlet 122 are formed at appropriate positions at the top side 902 and the bottom side 904 of the thermal pipe 118 for achieving an optimum flow of the liquid coolant. In the present embodiment, the top and bottom sides of the thermal pipe 118 are connected internally via the through-holes of the hollow waveguide 102. The ends of the hollow waveguide 102 and the thermal pipe 118 are coupled, as shown in Figure 9, so that the liquid coolant flows from the top side 902 of the thermal pipe 118 to the bottom side 904 of the thermal pipe entirely through the hollow waveguide 102. The design of the thermal pipe structure will not affect the RF circuit due to the RF shield formed by the hollow waveguide 102.

As shown in Figure 9, the thermal pipe 118 with the hollow waveguide 102 integrated within the thermal pipe 118 is filled with the liquid coolant. To maintain a homogenous dielectric filled inside the hollow waveguide 102, a liquid level 906 of the liquid coolant within the thermal pipe 118 is maintained at a level equal to or above the hollow waveguide 102 as shown in Figure 9. This ensures that the RF performance will not be affected as the dielectric inside the hollow waveguide 102 is homogeneous. In the present embodiment, the level of the liquid is at least above the through-holes on the

top portion of the sidewall 108 of the hollow waveguide 102. In an embodiment, the hollow waveguide is completely filled with the liquid coolant. The liquid coolant is therefore provided inside both the thermal pipe 118 and the hollow waveguide 102 and directly interacts with the RF circuit within the hollow waveguide 102 for cooling the RF circuit. An internal height 908 of the thermal pipe is also shown in Figure 9.

In the present embodiment, the liquid coolant used includes the 3M™ Fluorinert™ Electronic Liquid FC-40 (hereinafter FC-40). The FC-40 liquid coolant has a dielectric strength (at 0.1-inch gap) of 46 kV, a dielectric constant (at 1 kHz) of 1.9 and an electrical resistivity of 4.0×10^{15} (Ohm•cm). It should be appreciated that other suitable liquid coolants can be used. Generally, a lower dielectric constant and a higher electrical resistivity of the liquid coolant are preferred.

As illustrated above, therefore, the hollow waveguide 102 can be optimised independently to control the RF/EM wave, while the thermal pipe 118 can be optimised independently to control a flow of the liquid coolant for cooling the RF circuit within the hollow waveguide 102.

In summary, in the present embodiment, a rectangular hollow waveguide 102 designed with an array of through-holes formed on the top and bottom sides of the hollow waveguide is provided for cooling a RF circuit, such as a RF high power amplifier circuit. The RF high power amplifier circuit is integrated within the hollow waveguide 102 to support EM wave propagation in a lateral direction through the ends of the hollow waveguide 102. The hollow waveguide 102 is embedded within a thermal pipe 118 which allows liquid coolant to flow vertically through (i.e. in the present embodiment, from the top side to the bottom side) of the hollow waveguide 102. Both the lateral ends of the hollow waveguide 102 are sealed using a dielectric material so that the liquid coolant is contained within the hollow waveguide 102 while allowing RF/EM waves to propagate through the hollow waveguide 102.

Figure 10 shows a schematic of a system 1000 for cooling a radio-frequency (RF) circuit in accordance with an embodiment. The system 1000 is adapted to provide direct or immersive liquid cooling to the RF circuit, using the package 100 as described above.

The system 1000 comprises (i) a package 100, (ii) a liquid coolant reservoir 1002 configured to provide the liquid coolant to the package 100 for cooling the RF circuit and to receive the liquid coolant from the package, (iii) a pump 1004 configured to drive the liquid coolant from the liquid coolant reservoir 1002 to the package 100, and (iv) a radiator 1006 configured to cool the liquid coolant received from the liquid coolant reservoir 1002 prior to providing the liquid coolant to the package 100.

Figure 10 shows the circulation of the liquid coolant within the system 1000. The liquid coolant is pumped from the liquid coolant reservoir 1002 using the pump 1004 at 1008 and directed towards the radiator 1006 to be cooled at 1010. The cooled liquid coolant is provided to the package 100 at 1012 for cooling the RF circuit in the package 100. The liquid coolant having been used to cool the RF circuit then flows back to the liquid coolant reservoir 1002 which will be re-circulated to the radiator 1006 to be cooled and re-used to cool the RF circuit in the package 100. In the present embodiment, the liquid coolant is circulated at a flow rate of 10 L/min, although it should be appreciated that other suitable flow rates can be used. Generally, a higher flow rate of the liquid coolant, where appropriate taking into consideration other constraints of the system, provides a better thermal or cooling performance.

Figure 11 shows a schematic of a three-dimensional (3D) model 1100 of the package 100 used for 3D electromagnetic (EM) simulation in accordance with an embodiment.

The RF performance of the liquid coolant filled integrated hollow waveguide 1102 with the thermal pipe 1104 was simulated using a 3D EM simulator. In the present embodiment, Ansys HFSS (high-frequency structure simulator) was used as the 3D EM simulator but it should be appreciated that other 3D EM simulators, such as the CST Studio Suite and the EMPro 3D Electromagnetic Simulation Software etc., can be used. In the present 3D EM simulation model, two RF circuit boards 1106 each having two sets of back-to-back RF combiners were used. The RF combiners of the RF circuit boards 1106 placed within the hollow waveguide 1102 were simulated using back-to-back configuration. In this back-to-back configuration, two identical RF combiners are used for each RF circuit boards 1106, where each of the two identical RF combiners is connected at each end of the RF circuit board 1106 such that they are mirrored at the centre of the RF circuit board 1106. The 3D EM simulation model also included a

section of a standard WG-90 waveguide 1108 of 18 mm at both ends of the hollow waveguide 102, as shown in Figure 11.

Figure 12 shows a graph 1200 of simulated S-parameters for the back-to-back liquid coolant filled hollow waveguide 1102 using the 3D model of Figure 11 in accordance with an embodiment.

The graph 1200 shows that the hollow waveguide interconnect has an insertion loss 1202 (S21) of ~1.7 dB from the input to the output of the liquid coolant filled hollow waveguide 1102, and a return loss (S11) 1204 of better than ~ -15 dB from 9 GHz to 12 GHz. This covers most of the frequency of the X-band from 8 GHz to 12 GHz. The losses include the power RF combiners for four power amplifiers and is mainly due to the assumption that the liquid coolant has a loss tangent of 0.008.

Figure 13 shows a simulated three-dimensional (3D) thermal contour plot 1300 of the RF circuits by direct cooling using a package in accordance with an embodiment.

In the present simulation, a non-conductive electronic liquid coolant (fully fluorinated) having a turbulent flow convection rate of 10 L/min and a fluid inlet temperature of 25 °C was used for the direct cooling method of the present disclosure. The simulated three-dimensional (3D) thermal contour plot 1300 shows a maximum chip temperature 1302 of 53.6°C, wherein the ambient temperature is 25°C and the thermal resistance of R_{ja} is ~0.18 K/W. It is also simulated (not shown) that the direct cooling method of the present disclosure can dissipate 255 W with a temperature rise of 46 °C above the ambient temperature.

Comparing the direct cooling method of the present disclosure with a conventional metal cooling solution (see e.g. "Nai-Shuo Cheng, A. Alexanian, M. G. Case, D. B. Rensch and R. A. York, "40-W CW broad-band spatial power combiner using dense finline arrays," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 7, pp. 1070-1076, July 1999"), the present liquid coolant filled thermal solution results in a ~42 % cooling performance improvement and ~ 70% of power dissipation improvement.

Figure 14 shows a schematic of the RF circuit being integrated on a RF circuit board in a bare die using a flip-chip arrangement in accordance with an embodiment.

- In the present embodiment, for the flip chip configuration, the die is reconfigured using FOWLP (Fan Out wafer Level Packaging) 1402 so that a clearance height 1404 of the RF circuit's (in the present case, a monolithic microwave integrated circuit (MMIC) 1406) active surface to a substrate 1408 below can be increased using solder balls 1410 having a larger diameter. Particularly, by using bigger solder balls 1410, a larger clearance height 1404 of the active surface of the MMIC 1406 from the substrate can be provided to avoid capacitive loading effect from the substrate and to provide more space for the liquid coolant to flow through on this front-side 1412 of the MMIC 1406. At the same time, a backside 1414 of the MMIC 1406 (i.e. an opposite side to the front-side of the RF circuit) is deposited with a ground metal plane 1416. This allows maximum contact between the ground metal plane 1416 with the liquid coolant as the ground metal plane 1416 is fully exposed (or not having another layer or a substrate in close contact) in this FOWLP configuration, thereby improving a cooling efficiency in this flip-chip configuration.
- 15 The present disclosure therefore provides embodiments of a package and a system for cooling a RF circuit which provide alternatives and/or advantages in view of the existing art. Particularly, a novel high-power RF package having an integrated thermal solution is provided. In the present embodiment, a RF circuit board is provided vertically inside a rectangular hollow waveguide which is embedded inside a thermal pipe filled with a liquid coolant. The rectangular hollow waveguide has an array of through-holes formed on a top and a bottom portions of the sidewall of the hollow waveguide adapted to allow the liquid coolant to flow parallelly across the RF circuit board. The liquid level of the liquid coolant is maintained to be above the rectangular hollow waveguide to ensure dielectric homogeneity within the hollow waveguide to optimise RF performance of the hollow waveguide. Particularly, in the present embodiment, the hollow waveguide is enclosed within a larger thermal pipe (or package) which holds the liquid coolant. By maintaining the liquid level of the liquid coolant above the height (or the vertical dimension) of the hollow waveguide, it is ensured that the liquid coolant completely fills up the hollow waveguide. As exemplified in relation to Figure 9, in the present embodiment, the cross section of the thermal pipe of the present embodiment is larger than that of the hollow waveguide, and a centre of the cross section of the thermal pipe is approximately centred with a centre of the cross section of the hollow waveguide. This means that a larger volume of liquid than the volume of the hollow

waveguide is provided in the present embodiment when the liquid level of the liquid coolant is maintained above the height (or the vertical dimension) of the hollow waveguide. This helps to ensure that an internal volume of the hollow waveguide will still be completely filled with the liquid coolant even if the package is tilted or inverted.

- 5 In an embodiment, the rectangular hollow waveguide is sealed using a dielectric film at each open ends of the hollow waveguide to prevent the liquid coolant from flowing to the external standard waveguides, while allowing EM / RF waves to propagate laterally through the hollow waveguide. In an embodiment, as the high-power RF circuit is immersed inside the liquid coolant, and the liquid coolant is circulated externally to
- 10 maximise its cooling efficiency, the liquid cooling has a power dissipation performance improvement of 70% and a cooling performance improvement (thermal resistance) of 42% when compared with a conventional metal cooling thermal solution.

- Alternative embodiments of the invention include: (i) a cross-section of the hollow waveguide 102 and/or a cross-section of the thermal pipe 118 being of any shape and
- 15 this may include one of: a circular cross-section, a square cross-section, a rectangular cross-section, a hexagonal cross-section and an octagonal cross-section; (ii) the through-holes and an array pattern of the through-holes being not uniform on both sides of the hollow waveguide 102; (iii) the design of the through-holes (e.g. a diameter and a shape of the through-holes and/or a pitch between adjacent through-holes) can
- 20 be optimised (e.g. increasing a diameter of a through-holes or reducing a pitch between adjacent holes) to improve thermal performance of the package 100; (iv) the hollow waveguide 102 is integrated with the thermal pipe 118; (v) one or more RF circuit boards are integrated within the hollow waveguide 102; (vi) one or more through-holes can be designed on all sides, or any one or more side or portions of the sidewall
- 25 of the hollow waveguide 102 instead of at only the top and bottom sides of the hollow waveguide; (vii) the through-holes formed on one side of the hollow waveguide 102 being not aligned with the through-holes formed on another side (e.g. an opposite side) of the hollow waveguide 102; (viii) the liquid circulation inlet and the liquid circulation outlet being asymmetrical or not identical or not aligned; (ix) other suitable liquid
- 30 coolant having different dielectric constant (as compared to 1.9 measured at 1 kHz used in the present embodiment) and/or different electrical resistivity (as compared to an electrical resistivity of 4.0×10^{15} Ohm•cm) as long as the liquid coolant is not electrically conductive; (x) the RF circuit being positioned within the hollow waveguide

- 102 to enable the liquid coolant flowing through the hollow waveguide 102 to be at an angle to a longitudinal plane or a planar area of the RF circuit; (xi) different number of RF circuits and/or different numbers of RF combiners formed on each circuit board besides having two RF circuits being formed on each circuit board; (xii) different
- 5 numbers of circuit boards used beside using two circuit boards or four circuit boards; (xiii) different flow rates of the liquid coolant employed for flowing through the hollow waveguide 102 other than 10 L/min used in an embodiment; and (xiv) the through-holes on a portion of the sidewall 108 may not be identical to the through-holes on another portion of the sidewall 108 of the hollow waveguide 102.
- 10 Although only certain embodiments of the present invention have been described in detail, many variations are possible in accordance with the appended claims. For example, features described in relation to one embodiment may be incorporated into one or more other embodiments and *vice versa*.

Claims

1. A package for cooling a radio-frequency (RF) circuit, the package comprising:
a hollow waveguide having a first end, a second end, and a sidewall connecting
the first end and the second end to form an enclosure for the RF circuit, the first end
5 being opposite to the second end,
wherein the hollow waveguide has through-holes formed on one or more
portions of the sidewall, the through-holes being adapted to allow a liquid coolant to
flow through the hollow waveguide for cooling the RF circuit, and
wherein, in use, the hollow waveguide is completely filled with the liquid coolant,
10 and is adapted to propagate a RF signal from the first end to the second end of the
hollow waveguide.
2. The package of claim 1, wherein the through-holes includes two arrays of through-
holes formed on opposite portions of the sidewall.
15
3. The package of claim 2, wherein the opposite portions of the sidewall are uniformly
populated with the two arrays of through-holes and wherein a diameter and a shape of
each of the through-holes and a pitch between adjacent through-holes of the two
arrays of through-holes are identical.
20
4. The package of claim 3, wherein the diameter and the pitch are less than 0.1 of an
operating wavelength of the RF circuit.
5. The package of any one of the preceding claims, further comprising a dielectric film
25 being adapted to seal each of the first end and the second end of the hollow waveguide.
6. The package of claim 5, where the dielectric film includes a microwave material
having a dielectric constant (Dk) of 2.1 and a low loss tangent (Df) of 0.001 and a
thickness of 0.5 mm.
30
7. The package of claim 5 or claim 6, further comprising an electrically conductive
frame coupled to each of the first end and the second end of the hollow waveguide, the

electrically conductive frame having an opening with an area larger than a planar area of the dielectric film and is adapted to be centred with a centre of the dielectric film.

8. The package of any preceding claim, further comprising a thermal pipe adapted to
5 enclose the hollow waveguide and is in fluid connection with the hollow waveguide, the
thermal pipe having a liquid circulation inlet for receiving the liquid coolant to be
provided to the hollow waveguide and a liquid circulation outlet for returning the liquid
coolant from the hollow waveguide, the liquid circulation inlet and the liquid circulation
10 outlet being adapted to allow circulation of the liquid coolant through the hollow
waveguide for cooling the RF circuit.

9. The package of claim 8, wherein the liquid circulation inlet includes one or more inlet
holes and the liquid circulation outlet includes one or more outlet holes, at least one of
the one or more inlet holes and the one or more outlet holes is aligned to the through-
15 holes formed on the one or more portions of the sidewall of the hollow waveguide.

10. The package of claim 8 or claim 9, wherein the thermal pipe is isolated electrically
from the hollow waveguide.

20 11. The package of any one of the preceding claims, further comprising the RF circuit,
the RF circuit being positioned within the hollow waveguide to enable the liquid coolant
flowing through the hollow waveguide to be in a direction substantially in plane to a
longitudinal plane of the RF circuit.

25 12. The package of claim 11, further comprising a RF combiner input and a RF
combiner output operationally connected to the RF circuit, each of the RF combiner
input and the RF combiner output comprises a RF combiner circuit having multiple
tapered slots to couple the RF signal from the hollow waveguide to a two-dimensional
(2D) planar transmission line.

30 13. The package of claim 11 or claim 12, wherein the RF circuit is integrated on a RF
circuit board in bare die using either flip-chip or wire bonding.

14. The package of claim 14, further comprising one or more additional RF circuits being integrated on the RF circuit board.

15. The package of claim 13 or claim 14, further comprising one or more additional RF circuit board, each of the one or more additional RF circuit board having one or more further RF circuits.

16. The package of any one of the preceding claims, wherein a cross-section of the hollow waveguide includes one of: a circular cross-section, a square cross-section, a rectangular cross-section, a hexagonal cross-section and an octagonal cross-section.

17. A package for cooling a radio-frequency (RF) circuit, the package comprising:

a hollow waveguide having a first end, a second end, and a sidewall connecting the first end and the second end to form an enclosure for the RF circuit, the first end being opposite to the second end, and the first end and the second end of the hollow waveguide are each sealed using a dielectric film, wherein two arrays of through-holes are formed on opposite portions of the sidewall of the hollow waveguide, the through-holes being adapted to allow a liquid coolant to flow through the hollow waveguide for cooling the RF circuit; and

a thermal pipe adapted to enclose the hollow waveguide and is in fluid connection with the hollow waveguide, wherein a cross-section of the thermal pipe is larger than a cross-section of the hollow waveguide and having a centre being approximately centred with a centre of the cross section of the hollow waveguide, the thermal pipe having a liquid circulation inlet for receiving the liquid coolant to be provided to the hollow waveguide and a liquid circulation outlet for returning the liquid coolant from the hollow waveguide, the liquid circulation inlet and the liquid circulation outlet being adapted to allow circulation of the liquid coolant through the hollow waveguide for cooling the RF circuit, the thermal pipe being isolated electrically from the hollow waveguide,

wherein, in use, the hollow waveguide is completely filled with the liquid coolant, and is adapted to propagate a RF signal from the first end to the second end of the hollow waveguide.

18. A system for cooling a radio-frequency (RF) circuit, the system comprising:

the package of any one of the preceding claims;

a liquid coolant reservoir configured to provide the liquid coolant to the package for cooling the RF circuit and to receive the liquid coolant from the package;

5 a pump configured to drive the liquid coolant from the liquid coolant reservoir to the package; and

a radiator configured to cool the liquid coolant received from the liquid coolant reservoir prior to the liquid coolant being provided to the package.

10 19. The system of claim 18, wherein the liquid coolant is circulated at a flow rate of 10 L/min.

20. The system of claim 18 or claim 19, wherein the liquid coolant has a dielectric constant of 1.9 measured at 1 kHz and an electrical resistivity of 4.0×10^{15} Ohm·cm.