



(11)

EP 4 478 530 A1

(12)

EUROPEAN PATENT APPLICATION

(43) Date of publication:
18.12.2024 Bulletin 2024/51

(51) International Patent Classification (IPC):
H01P 5/08 ^(2006.01) **H01R 9/05** ^(2006.01)
H01R 24/40 ^(2011.01)

(21) Application number: **23179784.6**

(52) Cooperative Patent Classification (CPC):
H01P 5/085; H01R 9/0515; H01R 24/50;
H01R 43/02

(22) Date of filing: **16.06.2023**

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB
GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL
NO PL PT RO RS SE SI SK SM TR

Designated Extension States:

BA

Designated Validation States:

KH MA MD TN

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Remarks:

Amended claims in accordance with Rule 137(2) EPC.

(54) **ELECTRICAL CONNECTION TO PHOTONIC INTEGRATED CIRCUITS AND MODULES**

(57) A method of forming a direct electrical connection between a photonic integrated circuit (PIC) and a coaxial connector for a high-frequency or high-bandwidth connection of 50 GHz or more. The PIC has a planar transmission line with a track of sub-400 micrometer width. A blob of solder paste or electrically conductive adhesive is dispensed onto the track. The PIC is then moved relative to the coaxial connector to bring its con-

ductor pin into a bonding position in which an end length portion of the connector pin is in contact with the blob. The blob is then hardened while the connector pin is held in the bonding position to form a permanent electrical connection between the connector pin and the track to which it is to be connected. A high frequency electrical connection is thus made without the use of a bridging electronic integrated circuit (EIC).

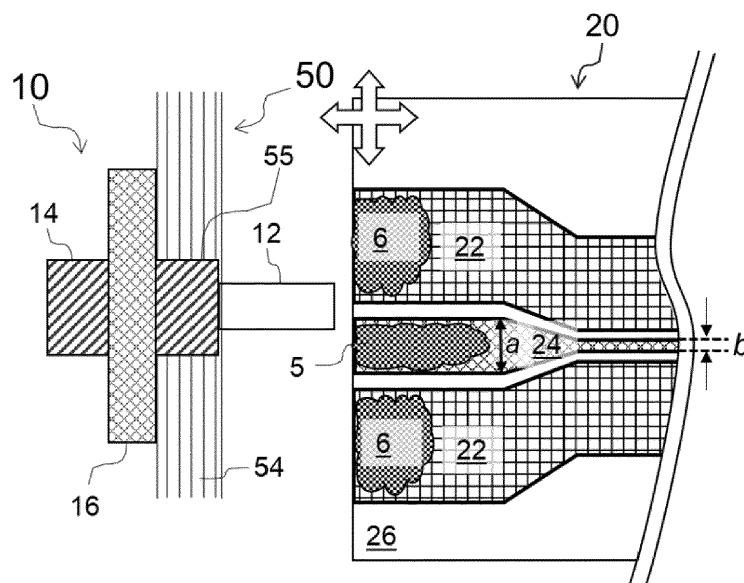


FIG. 11C

Description

BACKGROUND OF THE INVENTION

[0001] The invention relates methods of forming high-frequency electrical connections to photonic integrated circuits (PICs) and further relates to PIC modules electrically connected according to this method as well as uses of such PIC modules.

[0002] For applications such as telecommunications, sensing and quantum computing, it is often necessary to connect an electrical cable via a suitable coaxial connector to an electrode on a PIC so that an electrical signal can be conveyed to or from the PIC. An electrical signal to be input to a PIC might be for a drive or biasing electrode formed on the surface of the PIC, such as for an electro-optic modulator or laser source. An electrical signal to be output from a PIC might be an output signal from a photodiode or other optoelectronic device that is a component of the PIC. For external electrical interfacing, the PIC may be provided with a planar transmission line (PTL) such as a conventional coplanar waveguide (CPW) on one surface thereof. A CPW is formed of a signal track or electrode flanked by two ground tracks or electrodes in what is referred to as a ground-signal-ground (GSG) configuration. The electrical connection is formed by soldering a connector pin of a coaxial connector to the CPW signal track on the PIC.

[0003] For relatively low signal frequencies or bandwidths of 10 GHz, as were typical in the 2000s, a coaxial connector with a relatively large connector pin diameter of 1 mm can be used. Soldering a $\Phi 1$ mm connector pin onto a CPW signal track on the surface of the PIC is straightforward. SMA or K-type coaxial connectors are used. An example is shown in JP2011-015200A [1]. Over the last few decades, there has been a trend to ever higher RF frequencies and hence bandwidths. In recent years, frequencies ranging from 0 GHz (or DC) up to 50 GHz and into the W-band (75-110 GHz) and the D-band (110-170 GHz) have become increasingly important. As operating frequency increases, the connector pin diameter of the coaxial connector decreases. coaxial connector design is discussed in the literature [2, 3] and subject to the standard IEEE 287.1:2021 "IEEE Standard for Precision Coaxial Connectors at RF, Microwave, and Millimeter-Wave Frequencies". For example, a coaxial connector for broadband operation from DC up to 110 GHz may use a so-called 1.0 mm coaxial connector (W-type) with an internal connector pin diameter (facing the PTL) of, for example, 130 μm . In another example, a so-called 0.8 mm coaxial connector (also W-type) is used for broadband operation up to 145 GHz and this may have a connector pin diameter of less than 100 μm , e.g. 80 μm .

[0004] The reduction in connector pin diameter as one moves to higher frequencies creates challenges for the solder bonding. With connector pin diameters of less than about 200 μm , direct soldering is not generally possible and will not achieve the required mode matching and impedance matching. For the RF mode that is launched from the connector pin into the signal electrode on a PIC, one needs to balance two aspects: impedance matching and mode matching. The coaxial connectors are typically matched at 50 Ω (but not necessarily always at 50 Ω ; one can have 100 Ω or an open circuit), and so the connection from the connector pin must be made. A CPW then has to be impedance matched to 50 Ω . In addition, the mode must be tailored between the connector pin and the electrical signal electrode on the PIC, so the CPW is also used as a mode matching region.

[0005] To provide for adequate impedance and mode matching and to make it physically possible to solder on the connector pin, it has become standard practice when using connector pin diameters of less than about 200 μm to arrange an electronic integrated circuit (EIC) between the coaxial connector and the PIC. The EIC is provided with a PTL such as CPW for carrying the RF signal, so that the EIC acts as a bridge piece for the electrical transmission line between the coaxial connector and the PIC. A taper-down of the EIC CPW signal track allows it to be wide enough at its wide end, e.g. a width of greater than about 500 μm , to solder on the connector pin without difficulty. The narrow end of the EIC CPW signal track is then bonded to the PIC signal track using wire or ribbon bonds over an electrically insulating gap between the EIC and PIC. This approach for forming high frequency connections is disclosed in, for example, Muramoto et al 2004 [4], Macario et al 2014 [5] and Bach et al 2004 [6].

[0006] These three prior art examples are now discussed in turn with reference to schematic drawings.

[0007] Figure 1 is a schematic perspective drawing reproducing what is shown in Figure 1 of Muramoto et al 2004 [4]. The device is a semiconductor photodetector with a bandwidth of 80 GHz. The photodetector is formed in a PIC 20 that receives light 28 to be detected. The PIC 20 is based on an InP substrate 26 with InGaAs epitaxial layers forming the photodiode. A circular-section connector pin 12 of a coaxial connector extends through an aperture 55 in a sidewall 54 of the module housing. The module housing sidewall 54 is grounded. An EIC 30 is arranged between the PIC 20 and the connector pin 12. The EIC 30 is based on a quartz substrate 36 on which is formed by metallization a CPW 32, 34 in a GSG configuration. A CPW signal track 34 is flanked by two CPW ground tracks 32. The EIC CPW signal track 34 is tapered towards the PIC 20. The EIC CPW tracks 32, 34 are individually connected to corresponding PIC CPW signal and ground tracks 22, 24 via ribbon bonding wires 38. The connector pin 12 is bonded by a solder blob 5 to the EIC CPW signal track 34. The solder blob 5 lies on the surface of a length portion of the EIC CPW signal track 34 proximal the module sidewall 54 and embeds an end length portion of the connector pin 12. The EIC CPW ground tracks 32 are bonded by respective further solder blobs 6 to the inside surface of the grounded module housing sidewall 54.

[0008] Figure 2 is a schematic perspective drawing reproducing what is shown in Figure 1 of Macario et al 2014 [5]. A PIC 20 based on lithium niobate (LiNbO_3) accommodates an electro-optical modulator of a Mach-Zehnder interferometer design. The modulator has a bandwidth of 110 GHz. The PIC 20 is connected to a PTL using a coaxial connector 10 via a bridging EIC 30. The coaxial connector 10 has a connector pin 12 with a diameter of 130 μm . The connector pin 12 is surrounded by a connector shell 14 that is grounded. The coaxial connector 10 is secured to a module 50 by screwing it onto a module housing sidewall 54 where there is an aperture 55 such that the connector pin 12 of the coaxial connector 10 extends into the interior volume of the module 50. Light enters and leaves the Mach-Zehnder interferometer via an optical input 28 and an optical output 29 respectively. The Mach-Zehnder interferometer acts as an optical modulator actuated by a modulated electric signal. The electrical signal is applied to the PIC 20 via a CPW 22, 24 in a GSG configuration formed as a metallization layer on an upper surface of the PIC 20. The PIC CPW 22, 24 is formed by a signal electrode 24 flanked by two CPW ground tracks 22. The PIC 20 is arranged adjacent an EIC 30 which forms an intermediate connecting part between the coaxial connector 10 and the PIC 20. The EIC 30 is based on an alumina (Al_2O_3) substrate on which is formed by metallization a CPW 32, 34 in a GSG configuration, namely by a CPW signal track 34 and two CPW ground tracks 32. The EIC CPW signal track 34 is tapered towards the PIC 20. Adjacent the PIC 20, the EIC CPW tracks 34, 32 are individually connected to the corresponding PIC CPW signal and ground tracks 24, 22 via ribbon bonding wires 38. Adjacent the coaxial connector 10, the EIC CPW signal track 34 is soldered to the connector pin 12 by a solder blob 5 and the EIC CPW ground tracks 32 are soldered to the inside surface of the module housing sidewall 54 by respective solder blobs 6, the module housing 54 being at ground. After soldering, the length of the solder blobs 5, 6 from the end of the connector pin and the housing sidewall along the CPW tracks 34, 32 is about 400 μm . The coaxial connector 10 is specified with a 0.7-dB insertion loss and a 50 Ω impedance. Therefore, a CPW characteristic impedance of 50 Ω is required at both ends of the EIC 30 to minimize the RF return loss at the transitions from the coaxial connector 10 to the EIC CPW and from the EIC CPW to the PIC CPW. The diameter of the connector pin is 130 μm , whereas the width of the PIC CPW signal track 24 on the modulator in the launch section is 50 μm . Consequently, the EIC CPW signal track 34 has a taper section to ensure mode matching at both the connector-pin-to-EIC transition and the EIC-to-PIC transition.

[0009] Figure 3 is a schematic perspective drawing reproducing what is shown in Figure 2 of Bach et al 2004 [6]. The device is a semiconductor photodetector based on InGaAsP/InGaAs epitaxial layers on an InP substrate. The photodetector has a bandwidth of 100 GHz. The detector signal is output as an electrical signal to a coaxial cable specified up to 110 GHz. The photodetector is formed in a PIC 20 with an InP substrate 26 and including a waveguide 27. The PIC 20 is coupled via an air bridge to an EIC 30 via wire bonds 38. The EIC 30 is based on a quartz substrate 36 on which is formed by metallization a CPW 32, 34 in a GSG electrode configuration, namely of a CPW signal track 34 and two CPW ground tracks 32. The EIC CPW signal track 34 is tapered towards the PIC 20 and flanked by the two EIC CPW ground tracks 32. The EIC CPW tracks 34, 32 are individually connected to the corresponding PIC signal and ground tracks 24, 22 via bonding wires 38. To complete the package, a coaxial connector (not shown) is soldered by its connector pin to the EIC CPW signal track 34 and by its ground shield to the EIC CPW ground tracks 32 either directly or by a grounded module housing sidewall. The authors describe how the circuit elements of the photodetector, i.e., the p-i-n junction equivalent circuit, the air bridge between the PIC and EIC, and its impedance representation, the stray elements of the terminating resistors, and the EIC CPW taper, were modeled by a circuit simulator in conjunction with anticipated damping losses and small additional inductances of bonding wires in the final packaging. The aim of the simulation is to precompensate onchip for the known losses of the EIC CPW signal track 34 (which is 2mm long). These external losses were determined to be about 0.5 dB for frequencies of up to 100 GHz. The idea behind this approach is to introduce a reproducible control of on-chip impedance up to the coaxial connector in the packaging and to avoid scatter of inductive peaking due to the signal interconnections between the PIC CPW signal track 24, the EIC CPW signal track 34 and the coaxial connector pin. The authors thus consider mode matching that reduces the S11 parameter (the reflection) and also impedance matching to reduce those inductive parasitic behaviours coming from the wire bonding lines 38. The parasitic effects of the wire bonding steps, for example, increase the inductance of the entire transmission line, which is then translated into the measurements of the S21 with a peak at high frequencies, this being referred to by the authors as "*scatter of inductive peaking*".

SUMMARY OF THE INVENTION

[0010] According to one aspect of the disclosure there is provided a method of forming an electrical connection between a photonic integrated circuit and a coaxial connector, the method comprising:

- providing a photonic integrated circuit having a planar transmission line that includes at least one track;
- providing a coaxial connector with a connector pin having an end length portion dimensioned and disposed in the coaxial connector to be suitable for bonding to the planar transmission line;
- dispensing onto an area of the track an amount of a solder paste or an electrically conductive adhesive to form a

blob thereon; and, after said dispensing,
 moving the photonic integrated circuit relative to the coaxial connector to bring the end length portion of the connector
 pin into a bonding position in which the end length portion is in contact with the blob; and thereafter
 hardening the blob while the connector pin is held in the bonding position to form an electrical connection between
 the connector pin and the track.

[0011] In the above method, the order in which the pin alignment and the pin bonding are carried out is reversed compared to a conventional approach in that a blob of bonding material is dispensed onto the surface of the PIC at the location where the connector pin is to be bonded before the connector pin is brought into its bonding position. (An example of the conventional approach of aligning the connector pin and then bonding is documented in the Instruction Sheet for the Anritsu W1-103F Connector: <https://dl.cdn-anritsu.com/en-us/test-measurement/files/Manuals/Instruction-Sheet/10305-00010C.pdf> - see section 4 thereof [8].) An electrical connection can thus be formed directly between a planar transmission line on a PIC and the connector pin of a coaxial connector without the need for an intermediary EIC, even in the case of small diameter connector pin and/or a narrow width signal or ground track. The bonding between connector pin and PIC can be aided by visually-aided alignment under a microscope, e.g. to an accuracy of $\pm 10 \mu\text{m}$.

[0012] According to a further aspect of the disclosure there is provided a photonic integrated circuit that has been connected to a coaxial connector according to the above method.

[0013] According to a still further aspect of the disclosure there is provided a module assembled according to the above method.

[0014] According to another aspect of the disclosure there is provided a module containing a photonic integrated circuit, the module comprising:

a photonic integrated circuit comprising a planar transmission line that includes a track;

a coaxial connector with a connector pin; and

a blob of solder paste or electrically conductive adhesive in physical and electrically conductive contact with both an end length portion of the connector pin with a maximum cross-sectional dimension of equal to or less than 300 micrometres and a length portion of the track that has a width of equal to or less than 400 micrometers.

[0015] According to a still further aspect of the disclosure there is provided use of the above module to transmit a signal between a photonic integrated circuit and a coaxial connector at a frequency greater than at least one of: 50 GHz, 67 GHz, 75 GHz, 100 GHz, 110 GHz and 145 GHz, in particular between 110 and 170 GHz. For frequencies above 170 GHz, microwave waveguides can be used and with current technology can carry frequencies up to 300 GHz signals as discussed in Sekine et al 2017 [7]. In future, still higher frequencies can be expected.

[0016] In some embodiments of the above method, the blob is a blob of solder paste and optionally the method may further include heating to cause reflow of the solder blob before cooling to cause said hardening.

[0017] In other embodiments of the above method, the blob is a blob of electrically conductive adhesive and optionally the method may further include heating to cure the electrically conductive adhesive blob before cooling to cause said hardening.

[0018] In some embodiments, in said bonding position an end length portion of the connector pin is in physical contact with the track. In other embodiments, a small gap may be left between the connector pin and the track in said bonding position.

[0019] In certain examples, the track has a length portion with a width of less than one of: 400, 350, 300, 250, 200, 150, 130 and 100 micrometers defined by lateral edges thereof, and wherein the blob is formed on this length portion.

[0020] The blob preferably has a lateral extent that is confined so as not to extend beyond the lateral edges of the track.

[0021] In certain examples, the end length portion of the connector pin has a maximum cross-sectional dimension equal to or less than one of: 300, 250, 200, 150, 130 and 100 micrometers.

[0022] In certain embodiments, said dispensing of solder paste or electrically conductive adhesive is done through a dispensing nozzle to dispense the blob with a positional accuracy of, for example, ± 10 micrometres.

[0023] The method may further comprise: providing a module with a housing; and securing the coaxial connector to the housing and optionally also securing the coaxial connector to the module housing prior to said moving. In certain examples, the module housing comprises at least one sidewall and the coaxial connector is secured to an outside surface of said sidewall at a position in which said sidewall has an aperture so that the connector pin is accessible from inside the module housing.

[0024] In certain embodiments, in the above module, the track on which the blob is formed has a further length portion with a further width that is less than said width, said length portion and said further length portion being interconnected by a tapered length portion of reducing width.

[0025] In certain examples of the above module, the maximum cross-sectional dimension, e.g. a diameter in the case of a circular section connector pin, is equal to or less than one of: 250, 200, 150, 130 and 100 micrometres.

[0026] In certain examples of the above module, said length portion of the track accommodating the blob has a width of equal to or less than one of: 350, 300, 250, 200, 150, 130 and 100 micrometers.

[0027] For many commercially available coaxial connectors, the connector pin will be cylindrical and thus have a circular cross-section. Its width is thus specified by a diameter. Other coaxial connectors may have different connector pin shapes, such as semi-circular, rectangular or square. With embodiments of the invention, it is possible to connect connector pins with the small diameters (or other maximum cross-sectional dimension in the case of non-cylindrical connector pins) onto narrow tracks of a high-frequency planar transmission line. Most commercially available high-frequency coaxial connectors have small diameter connector pins, where for example pin diameter of 300 micrometers are typical of 40 GHz coaxial connectors, 250 micrometers for 50 GHz and 130 micrometers for 90 GHz coaxial connectors. Moreover, most high frequency planar transmission lines as found on PICs have narrow widths, e.g. equal to or less than one of: 400, 350, 300, 250, 200, 150, 130 and 100 micrometers.

[0028] This form of bonding process and direct connection between connector pin and PIC planar transmission line can lead to one or more of the following advantages:

- reduction in the complexity of the bonding process
- reduced failure rate to improve assembly yield
- reduced assembly cost
- lower signal propagation losses at the electrical connection owing to the direct bonding without the presence of an intermediate EIC and associated wire/ribbon bonding between the EIC and PIC
- simplified impedance matching, since with small width planar transmission lines of width less than 150 μm , impedance matching can often be achieved with suitable design of the PIC (e.g. signal track tapering and materials choice of the PIC and tracks). The tapering of the signal track on the PIC can be used to balance the capacitance and inductance of the signal at such high frequencies. In some cases, it is possible to dispense altogether with an external impedance matching circuit with adjustable inductors and capacitors.

[0029] Engineering the impedance matching is done by considering and where possible choosing the materials that are used along the entire transmission line and by the geometry of the entire transmission line, i.e. from PIC to EIC to coaxial connector and to cable. Different materials have different RF losses. The RF loss depends on the RF absorption spectrum of the material, the aim being to have the lowest possible absorption coefficient for transmission of RF signals. The RF loss also depends on the dielectric constant of the material at the corresponding RF frequency. The impedance matching at 50 Ω can be modelled by analytical solutions or simulations. Regarding geometry, the ability to bond a small diameter connector pin directly to a small width track on a PIC's planar transmission line allows higher frequency microwave signals to be transmitted. In particular, the removal of the requirement to use a bridging EIC between the PIC and connector pin reduces the impedance of the planar transmission line, since a tapered EIC signal track is no longer present.

[0030] It is to be understood that the microwave electrical connection can be used as either an output from or input to the PIC as needed for the application at hand. For example, an electro-optic modulator would need an electrical input into a PIC, while a photodetector integrated as a component of the PIC would need an electrical output from the PIC.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031] This invention will now be further described, by way of example only, with reference to the accompanying drawings.

Figure 1 is a schematic perspective drawing of a prior art photodetector with a bandwidth of 80 GHz according to Muramoto et al 2004 [4].

Figure 2 is a schematic perspective drawing of a prior art electro-optic modulator with a bandwidth of 110 GHz according to Macario et al 2014 [5].

Figure 3 is a schematic perspective drawing of a prior art photodetector with a bandwidth of 100 GHz according to Bach et al 2004 [6].

Figure 4 is a schematic side view of a conventional coaxial cable.

Figure 5 is a schematic side view of a conventional coaxial connector for terminating a coaxial cable as shown in Figure 4.

Figures 6A and 6B are schematic side view of a conventional coaxial connector of the flange package type and of the sparkplug type respectively.

Figures 7A to 7F are schematic cross-sectional side views of some known planar transmission line structures.

Figure 8 is a schematic plan view of a module that accommodates a PIC that is electrically connected to a coaxial connector mounted to one of the module's sidewalls.

Figures 9 and 10 are schematic plan and perspective views showing the electrical connection between a coaxial connector and a PIC according to an embodiment of the invention.

Figures 11A to 11D are schematic plan views to illustrate certain stages in an assembly method for forming an electrical connection between a PIC and a coaxial connector according to an embodiment of the invention.

Figure 12 is a schematic plan view of an example device comprising a PIC incorporating a high-frequency electro-optical modulator with a direct electrical connection to a coaxial connector.

Figure 13 is a schematic plan view of an example device comprising a PIC incorporating a high-bandwidth photo-detector with a direct electrical connection to a coaxial connector.

Figure 14 is a schematic plan view of an example comprising a PIC incorporating an optical transceiver in which an electro-optical modulator acting as transmitter and a photodetector acts as receiver, both transmitter and receiver having respective direct electrical connections to respective coaxial connectors.

DETAILED DESCRIPTION

DEFINITIONS

[0032] Bandwidth: Bandwidth is a frequency range over which a signal extends or can be transmitted defined by the difference between upper and lower frequencies in a continuous band of frequencies. The bandwidth of an electrical transmission line typically spans from DC, i.e. 0 GHz, as the lower frequency up to a finite upper frequency (for example, a value expressed in GHz). Across the bandwidth, the signal may experience some variation in transmissivity as defined by a signal amplitude decrease, i.e. attenuation, of up to a certain amount from the maximum signal amplitude with a 3 dB drop-off from the maximum being a common definition for electrical signals.

[0033] Coaxial connector: A coaxial connector for operating at RF, microwave or millimeter-wave frequencies, in particular coaxial connectors for operating in the RF frequency region that are compliant with the standard IEEE 287.1-2021 "IEEE Standard for Precision Coaxial Connectors at RF, Microwave, and Millimeter-Wave Frequencies". However, we include coaxial connectors according to other standards and also coaxial connectors that are not compliant to any particular standard especially having regard to the fact that new connector formats and standards continue to be developed as operating frequencies increase, e.g. the relatively recently developed 1.0 mm and 0.8 mm connector formats. A male coaxial connector terminates the cable with a connector pin. The connector pin usually has a circular cross-section and is specified with a diameter but the connector pin may have some other cross-sectional form such as semi-circular, rectangular or square or indeed any arbitrary shape.

[0034] Coplanar Waveguide (CPW): A coplanar waveguide is a type of planar transmission line which conveys high frequency signals and can be incorporated as a component of an EIC, PIC or another chip, substrate or circuit board. A CPW is formed by a patterned layer of conductive material arranged on a surface of a chip, substrate or circuit board, such as an EIC or PIC. The conductive material layer typically consists of a signal track and adjacent ground tracks arranged on one face of the substrate. This is referred to in the art as a ground-signal-ground (GSG) configuration or sometimes a cold-hot-cold configuration. The conductive material is most commonly a metal. The CPW may additionally include a further layer of conductive material arranged on the opposite side of the substrate to form a ground plane, such a CPW being referred to as a conductor-backed CPW (CBCPW).

[0035] D-band: The frequency range of 110-170 GHz or equivalent wavelength range of 2.73-1.76 mm.

[0036] Dimensions: Numerical limits and ranges to dimensions and frequencies, such as less than 150 μm or between 110 and 170 GHz, are to be interpreted exactly when construing the claims and not rounded up or down using significant figures, decimal places or otherwise.

[0037] Electrically Conductive Adhesive (ECA): Electrically conductive adhesive comprises particles that are electrically conductive (e.g. a conductive metal such as silver, gold, nickel or copper, or graphite) dispersed in a matrix of a sticky substance (e.g. a synthetic resin or elastomer), a one-part or two-part epoxy, or silicone. The sticky substance is present in sufficiently low quantities (e.g. <20% by weight) in relation to the electrically conductive particles that the adhesive is electrically conductive through a conductive path being provided through the electrically conductive particles.

[0038] Electronic Integrated Circuit (EIC): The term EIC is used specifically to refer to a chip that comprises an electrical circuit, in some cases with a very low scale of integration, that is designed to be paired with a PIC, typically to provide an electrical interface from one or more electrodes on the PIC to one or more external electrical lines. A paired EIC and PIC may have comparable physical sizes and/or scales of integration.

[0039] Photonic Integrated Circuit (PIC): A PIC is a chip that comprises multiple optical and/or optoelectronic components, the components typically being interconnected within the chip by optical waveguides. Waveguides terminated with a grating coupler can also be used to couple light into and out of the PIC as desired. A PIC is formed by depositing layers on a substrate with the aid of lithography for defining the lateral structure. Common substrates for PICs are silicon, other semiconductor crystals such as gallium arsenide or indium phosphide, silica and certain nonlinear crystal materials such as lithium niobate (LiNbO₃), 2D materials or any other material that exhibits the Pockels effect such as electro-optic polymers, chalcogenides, potassium titanate phosphate (KTiOPO₄, or KTP), or barium titanate (BaTiO₃), for example. The substrate material is paired with the materials system that is desired for the PIC, the choice being based on factors such as the wavelength(s) of operation and the type of components (e.g. passive only, or active) in the circuit.

[0040] Planar Transmission Line (PTL): A planar transmission line comprises flat electrically conductive material patterning, typically metal, arranged on a dielectric material, commonly a substrate of some kind, e.g. for a PIC or EIC, or a printed circuit board (PCB), wherein the planar transmission line is specified to carry a high-frequency signal in the RF or microwave frequency ranges, which may be a digital or analog signal.

[0041] Radio frequency (RF): The frequency range of 1-1000 GHz or wavelength range of 300-0.3 mm.

[0042] Solder: Solder is a metal alloy for bonding metal workpieces to form an electrically conductive connection, the metal alloy having a suitably low melting point (at atmospheric pressure) which can be specified as being below 183°C. Indium solder is a popular example.

[0043] Solder paste: Solder paste consists of powdered solder suspended in a flux paste. The flux holds components in place until the soldering reflow process melts the solder elements.

[0044] W-band: The frequency range of 75-110 GHz or equivalent wavelength range of 4-2.7 mm.

DESCRIPTION OF EMBODIMENTS

[0045] It will be clear to one skilled in the art that many improvements and modifications can be made to the foregoing exemplary embodiment without departing from the scope of the present disclosure.

[0046] When referring to connectors by their frequency band, e.g. a W-band connector, this means the connector is specified to operate across the specified frequency band, e.g. 75-110 GHz for a W-band connector. However, it will be understood that the connector will also operate successfully at lower frequencies, e.g. below 75 GHz in the case of a W-band connector.

[0047] Figure 4 is a schematic side view of a conventional coaxial cable 60 suitable for operation at RF frequencies, in particular at frequencies at or above 50 GHz, such as the W-band or D-band. The coaxial cable 60 comprises a core conductor 62, e.g. solid copper, an insulator 64, e.g. polyethylene (PE), surrounding the core conductor 62, a conductive shield 66, e.g. copper braid or mesh, surrounding the insulator 64 and an outer insulating jacket 68, e.g. polyvinyl chloride (PVC), surrounding the conductive shield 66.

[0048] Figure 5 is a schematic side view of a conventional coaxial connector 10. The coaxial connector 10 is designed to operate in the RF frequency range and to terminate a compatible coaxial cable 60 as shown in Figure 4. The illustrated connector is male. The coaxial connector 10 comprises a connector pin 12 for forming an electrical connection with the core conductor 62 of the coaxial cable 60. The connector pin 12 typically has a smaller diameter, $\Phi 1$, at its internal end length portion (the end that is soldered or adhered to the trace, e.g. of a PTL) and a larger diameter, $\Phi 2$, at its external end length portion (the end that connects to the cable). The coaxial connector 10 further comprises a grounded connector shell 14 and a mounting flange 16. For ease of depiction, the ends of the connector pin 12 are shown extending beyond the ends of the connector shell 12 but this may or may not be the case. Coaxial connectors are usually manufactured to comply with the Standard IEEE 287.1-2021, the contents of which is incorporated herein by reference. This standard defines the external diameter of the connector pin but not the internal pin diameter. The dimensions (and cross-section) of the connector pin at its internal end are therefore chosen by the manufacturers; typically to be compatible with PTL dimensions of popular EICs and PICs.

[0049] Below is a table listing some example connector types alongside their specified upper frequencies and some dimensions that are relevant for the present description.

Defined in IEEE 287				Not defined in IEEE 287
Connector name	Recommended upper frequency (GHz)	Inside diameter of outer connector shell (outer Φ mm)	External pin (Φ 2 mm)	Internal pin (Φ 1 mm)
3.5mm	33.0	3.5	0.927	0.500
2.92mm	40.0	2.92	0.914	0.300
2.4mm	50.0	2.4	0.511	0.250
1.85mm	67.0	1.85	0.511	0.250
1.35mm	90.0	1.35	0.290	0.130
1mm	110.0	1	0.250	0.130/0.127
0.8mm	145.0	0.8	0.200	0.127

[0050] In the above table, the stated values of internal pin diameter Φ 1 are known values from popular manufacturers. The stated values of external pin diameter Φ 2 and inside diameter of the connector shell 14 are as prescribed in IEEE 287. It is further noted that some coaxial connector manufacturers provide a separate sleeve or pin extension piece that is pushed on to the internal end of the connector pin and it is the distal end of this extension piece that is soldered or adhesively bonded to the track of the PTL.

[0051] **Figure 6A** is a schematic side view of a conventional coaxial connector 10 of the flange package type mounted onto a sidewall 54 of a module 50. The mounting flange 16 is provided with two threaded holes by which the coaxial connector 10 can be screwed to a module sidewall 54 at a position in which the sidewall has an aperture 55, i.e. a through hole, so that the connector pin 12 is accessible from inside the module housing. The coaxial connector mounting flange 16 may be electrically connected to the conductive shield 66 of the coaxial cable 60, thereby to provide ground/earth shielding.

[0052] **Figure 6B** is a schematic side view of a conventional coaxial connector 10 of the sparkplug type mounted onto a sidewall 54 of a module 50. A sparkplug coaxial connector differs from a flange package coaxial connector in that the mounting flange 16 is threaded, i.e. forms a male thread, and can thus be screwed into a suitable female thread formed, for example, on the inner surface of the module sidewall aperture 55.

[0053] **Figures 7A to 7F** are schematic cross-sectional side views of some known PTL structures. Thick lines show electrode tracks (sometimes called traces). The stippled area is a dielectric material forming a substrate. Figure 7A is a microstrip with a single top conductor for the signal track and a ground formed over the underside of the substrate. Figure 7B is a CPW as discussed further above. Figure 7C is a CBCPW also as discussed further above. Figure 7D is a differential line (sometimes called slotline) with two tracks side-by-side on one surface of the substrate. Figure 7E is a stripline which has an embedded signal track and two grounds formed over the top side and bottom side of the substrate. Figure 7F is an embedded differential line with two embedded tracks arranged side-by-side buried within the substrate and two grounds formed over the top side and bottom side of the substrate. For more details of PTL structures we refer to Chapter 3.3 of "*Microwave and RF Design, Volume 2: Transmission Lines*" by Michael Steer, ISBN 13: 9781469656922, the contents of which is incorporated herein by reference. Embodiments of the invention involve solder or adhesive bonding an internal connector pin of a coaxial connector to a track of a PTL structure, which includes but is not limited to any of those shown in Figures 7A to 7F. In the case of bonding the connector pin to an embedded track, such as in Figure 7E or 7F, this may be done through an end face of the substrate or be possible from above or below, e.g. if a pit or via is etched partly or wholly through the substrate to expose a surface portion of the embedded track for solder bonding or adhesive bonding. In PTL structures, it is usually the case that the signal track is shielded by one or two ground tracks - either in the same plane on each side as in a CPW, or above and below as in a stripline, or on just one side as in a microstrip or differential line.

[0054] **Figure 8** is a schematic plan view of a module 50 after packaging according to an embodiment of the invention. The module 50 comprises a module housing 52 with sidewalls 54. One of the sidewalls has an aperture 55 for mounting a coaxial connector 10 that terminates a coaxial cable 60. Components are mounted inside the module 50 on a component mounting board 56. A PIC 20 is mounted on the component mounting board 56.

[0055] **Figures 9 and 10** are schematic plan and perspective views of a part of Figure 8 to show more detail. The coaxial connector 10, which is illustrated by way of example as being of the sparkplug type, has a mounting flange 16 which is threaded and is screwed into a matching thread on the inner surface of the module sidewall aperture 55. The sidewalls 54 of the module 50 are grounded. The coaxial connector 10 further comprises a grounded connector shell

14 that is arranged around a connector pin 12. The connector pin 12 extends into and is accessible from the interior of the module housing 52. Supported by a suitable substrate 26, the PIC 20 incorporates a CPW comprising a signal track 24 for conveying the signal and respective ground tracks 22 which are arranged either side of the signal track 24. The signal connection is made by a blob 5 of solder paste or ECA arranged on the surface of the PIC 20 and extending to embed an end length portion of the connector pin 12. The PIC 20 is mounted on the component mounting board 56. The blob 5 is confined to, i.e. does not spread beyond, the lateral extent of the Signal track 24 on which it is arranged. The Signal track 24 has a width 'a' over its length portion where the blob 5 is located. The two ground connections are made by respective blobs 6 of solder paste or ECA as schematically illustrated to bond respective ground tracks 22 to the inner surface of the grounded module sidewall 54. The end face of the PIC 20 located proximal to the module sidewall 54 is offset from the sidewall surface by a gap, G, of between 1-10 μm . Larger gaps would also be possible, e.g. up to 100, 200, 300, 400 or 500 μm . It is also possible that the PIC 20 is butted up against the surface of the module sidewall 54 to be in physical contact therewith, i.e. gap $G = 0$. The end of the PIC 20 distal to the coaxial connector 10 is connected to an optional external impedance matching circuit with adjustable inductors and capacitors (not shown), e.g. for impedance matching at 50 Ω . Although the PIC 20 can be designed to provide some impedance matching to the coaxial cable 60, an additional external impedance matching circuit is often also needed. The signal Signal track 24 is illustrated as incorporating a taper which tapers the width of the Signal track 24 down from a larger width 'a' proximal the coaxial connector 10 to a smaller width 'b'. Such a taper is beneficial to allow the direct bond between the connector pin 12 and the Signal track 24 to be formed in a region of the Signal track 24 that has a greater width 'a' than the narrower length portion of the signal track with width 'b'. With the precision pin positioning and bonding method according to embodiments of the invention, the width 'a' can be less than 200 μm , for example in the range between 150 μm and 200 μm . Away from the bond that forms the microwave electrical interface, the Signal track 24 tapers down to a width 'a' of, for example, less than 150 μm or less than 100 μm . A greater width 'a' for the solder or ECA bond can be helpful because it is difficult to form smaller bonds reliably with current state-of-the art bonding equipment.

ASSEMBLY METHOD

[0056] Figures 11A to 11D are schematic plan views to illustrate certain stages in an assembly method according to an embodiment of the invention for assembling the coaxial connector 10 and the PIC 20 into the module 50.

[0057] For the assembly there is provided a coaxial connector 10, a module 50, a mounting board 56 and a PIC 20. Figure 11A is a schematic plan view of the PIC 20 as provided for the assembly.

[0058] The coaxial connector 10 is secured to the module sidewall 54 as shown in Figure 6A or 6B.

[0059] The PIC 20 is processed to deposit blobs of solder paste or ECA onto each of the signal and ground tracks 24, 22 to form respective blobs 5, 6. Figure 11B is a schematic plan view of the PIC 20 after deposition of the blobs 5, 6. As illustrated, the blob 5 on the signal track 24 is located on the wider end portion of the signal track 24, which has a width 'b'. The blobs 6 on the ground tracks are also located at the same end of the PIC 20 adjacent an end face thereof.

[0060] The PIC 20 is then brought into position relative to the connector pin 12 for bonding. Figure 11C is a schematic plan view of the pre-soldered or pre-adhered PIC 20 of Figure 11B as it is being brought into alignment with the coaxial connector 10, as schematically shown by the arrows. For the alignment, the PIC 20 is manoeuvred via a suitable multi-axis translation stage (not shown) until an end length portion of the connector pin 12 is aligned with, and lying above, the end portion of the signal track 24 of width 'a'. The alignment is then completed by lowering the connector pin 12 into the blob 5 until the underside of the connector pin 12 is in physical contact with the upper surface of the signal track 24. Physical contact between the connector pin 12 and signal track 24 gives the connection maximum mechanical stability in the finished product and thereby maximize lifetime. As an alternative to physical contact, a small gap can be left between the bottom of the connector pin 12 and the PIC surface, e.g. between 10 - 100 μm . An end length portion of the connector pin 12 is thus lowered into a bonding position in which at least the underside of an end length portion of the connector pin 12 is brought into contact with the blob. An end length portion of the connector pin 12 thus becomes partly or wholly embedded in the solder blob 5 (or adhesive blob 5) or is ready to do so upon subsequent heating in case that reflow soldering is used. In case of soldering, the blob 5 is in a non-hardened state during this stage of the alignment process, i.e. either a solder paste as dispensed or molten. The alignment should be accurate to approximately $\pm 10 \mu\text{m}$ at least in the lateral direction perpendicular to the direction of extent of the connector pin 12 and the signal track 24. In the case of a solder bond, the solder blob 5 as deposited on the PIC 20 may optionally be allowed to freeze into a solid state before the alignment takes place, in which case it must be melted for the final part of the alignment process so that the blob 5 becomes 'wetable' and can thus coalesce around at least the underside of the connector pin 12 to leave an end length portion of the connector pin 12 partially or wholly embedded in the solder blob 5. This solder melting can be achieved by local reheating. On the other hand, in the case of bonding with an ECA, the hardening process is a one-way process and relatively slow, so the blob of adhesive will remain in a non-hardened state between when it is dispensed and when the alignment is carried out to embed the connector pin 12. The bonding material blob 5 is required to have an extent, in particular a lateral extent, that is confined to within the area of the signal track 24 as

defined by its width 'a'. The bonding material is therefore to be dispensed with a positional accuracy of approximately $\pm 10 \mu\text{m}$ and moreover dispensed in an amount and with a viscosity that ensures that the bonding material does not flow beyond the boundaries of the signal track 24 before it solidifies.

[0061] Figure 11D is a schematic plan view after the PIC 20 has been brought into its bonding position with the coaxial connector 10. In this bonding position, the 'signal' bump 5 has coalesced around an end portion of the connector pin 12. At the same time, each of the 'ground' bumps 6 has, through wetting, i.e. surface tension, spread over an area on the inside surface of the module housing sidewall 54, the module sidewall 54 being grounded. The blobs 5, 6 are then allowed to harden while the connector pin is held in the bonding position. In the case of solder, molten solder naturally cools down and freezes. In the case of ECA, the curing into a solid state can either be done passively, i.e. by just waiting (cold curing), or actively by heating (hot curing) or illumination (e.g. UV-induced cold curing).

[0062] Once the soldering or adhesive bonding process has been completed, the electrical connections between the PIC 20 and coaxial connector 10 are now made as shown in Figures 9 and 10.

[0063] The soldering or adhesive bonding process is monitored through visual inspection, e.g. using automated optical inspection (AOI), to achieve manufacturing tolerances of $\pm 10 \mu\text{m}$. A visual inspection system can be used as an aid to controlling the amount of solder paste or ECA that is dispensed. A visual inspection system can be used as an aid for alignment between the PIC 20 and connector pin 12 using suitable precision motion stages to achieve accurate positioning of the connector pin 12 above the surface of the PIC 20 in three dimensions with an accuracy of $\pm 10 \mu\text{m}$ in each dimension. Visual inspection can be either done directly on the features of interest, e.g. the connector pin 12, solder bump 5, PIC 20 or by using one or more alignment marks. A set of multiple microscopes viewing at different angles can be used.

[0064] With a PIC signal track width of $\leq 400 \mu\text{m}$, it is possible to engineer impedance matching between the PIC signal track and the PTL through tapering the signal track and through a suitable materials choice for the signal track. The inductance and/or capacitance adjustment provided by a suitable impedance matching circuit is simplified. The impedance matching circuit may be integrated with the PIC, provided as a separate electrical impedance matching circuit or an external impedance matching circuit.

[0065] In summary, we have described in the above detailed description a method of forming a direct electrical connection between a PIC and a coaxial connector for a high-frequency or high-bandwidth connection of 50 GHz or more. The PIC has a PTL with a track of sub-400 micrometer width. A blob of solder paste or ECA is dispensed onto the track. The PIC is then moved relative to the coaxial connector to bring its connector pin into a bonding position in which an end length portion of the connector pin is in contact with the blob. The blob is then hardened while the connector pin is held in the bonding position to form a permanent electrical connection between the connector pin and the track to which it is to be connected. A high frequency electrical connection is thus made without the use of a bridging EIC.

VARIANTS

[0066] In the above detailed description, embodiments of the invention have been mainly described and illustrated with reference to a CPW PTL. It will be understood that any type of PTL could be used, more especially but not exclusively any of the types shown in Figures 7A to 7F.

[0067] In the above detailed description, we described the signal track on the PIC as being tapered from a width 'a' where the microwave electrical connection is made to a width 'b'. In other embodiments, the taper of the signal track on the PIC may be omitted to provide a signal track 24 of constant width, e.g. a constant width of between $150 \pm 10 \mu\text{m}$ and $200 \pm 10 \mu\text{m}$. Moreover, it is possible for the signal track to have its microwave electrical connection formed in a wider part and then taper down to a narrower part, i.e. taper in the opposite way.

[0068] In the above detailed description, we illustrated the case where the microwave electrical connection is formed close to the edge of the PIC, e.g. a cleaved edge. In other embodiments, the microwave electrical connection could be formed well away from the edge of the PIC, which may be necessary for PICs with a higher level of integration requiring multiple microwave electrical connections over different areas on the chip surface, e.g. a transceiver PIC with both modulators and photodetectors.

[0069] In the above detailed description, we described a GSG CPW configuration. The GSG assembly method described above can readily be extended to GSGSG CPWs (i.e. two signal lines and two connector pins). The GSG assembly method described above can also be varied by omitting one ground connection to become a GS assembly method.

[0070] A further variation is to make the ground connection through the PIC (e.g. by creating one or more vertical vias that are connected electrically to the module housing or a subassembly) in which case a ground connection through the coaxial connector could be omitted. Generally, as mentioned above, forming the ground connections and grounding the PIC is straightforward and there are various options.

[0071] In the above detailed description, the electrical connection of the ground tracks to the coaxial connector is done together with and in a similar way as the signal track. For many types of PTL, it will however be the case that the ground

tracks can be made much wider than the signal track. As such, making the connections to the ground tracks need not be done according to methods embodying the invention, since it will usually be possible to make the ground tracks wide enough to allow them to be connected using a prior art soldering method as described in the introduction. For example, the specific example described above could be modified as follows. With reference to Figure 11B, only blob 5 would be deposited. With reference to Figure 11D, only the signal connection would be made at this point in the assembly. After the stage in the assembly illustrated in Figure 11D, the ground track connections would be made by dispensing solder paste or ECA onto each of the ground tracks 22 to form respective blobs 6.

[0072] In the above detailed description, the connector pin is always described as being connected to the signal track. However, although unusual, it is sometimes the case that the connector pin is connected to a ground track.

SOLDER & CONDUCTIVE ADHESIVES

[0073] Suitable methods of solder paste dispensing are described in US 6,543,677 [9] and Thum et al 2022 [10].

[0074] Suitable precision fluid delivery systems and dispensing handlers and dispensing nozzles are available from NSW Automation Sdn Bhd of Bayan Lepas, Penang, Malaysia.

[0075] Feature sizes as small as 5 μm are achievable with current solder dispensing methods, e.g. solder bump diameter, or solder track width.

[0076] The lower limit of the feature size is dictated most likely by the achievable dimensions of the solder paste according to the standard IPC J-STD-001 (see table below) or perhaps the positional precision of the equipment (translation stages, microscope resolution) but the equipment will usually have better precision of, for example, 1-2 μm .

IPC Type	Size Range (μm)
T3	25-45
T4	20-38
T5	15-25
T6	5-15

[0077] Suitable solders include the lead-free solder pastes commercially available from Indium Corporation of Clinton, New York, US. The soldering process may use reflow. The PIC/connector assembly is warmed up (pre-heat) and then maintained at an elevated temperature (thermal soak). The PIC may be heated, for example, by illumination with infrared light or blowing of hot air or in an oven. The solder paste is dispensed on the PIC track to be bonded (solder dispensing), which may be before or after the pre-heat or before or after the thermal soak. The connector pin is brought into the bonding position (alignment/positioning), this taking place after the solder dispensing. In the bonding position the solder paste blob is in contact not only with the PIC track but also an area on the connector pin surface. The temperature of the PIC is then further elevated (reflow) until the solder paste deposited on the PIC track becomes molten, i.e. liquid. The molten solder exhibits wetting, i.e. the molten solder has a contact angle of less than 90 degrees on the PIC track and connector pin surfaces that it is in contact with, and so spreads to form an intimate electrically conducting contact between the track and pin. The PIC is then cooled, actively or passively, so the solder solidifies to form the solder joint (cooling).

[0078] Suitable commercially available ECAs are marketed under the registered trade mark LOCTITE and sold by Henkel AG & Co of Düsseldorf, Germany. These include one- and two-part epoxy adhesives, silicone adhesives, and heat cure adhesives. A suitable commercially available two-part epoxy ECA is marketed under the registered trade mark EPO-TEK H20E which is based on silver and available from Epoxy Technology Europe GmbH. EPO-TEK H20E has a specified curing time of 10 minutes at a temperature of 140°C in a normal atmosphere. The adhesive bonding process proceeds by dispensing the ECA on the PIC track to be bonded (adhesive dispensing). The connector pin is brought into the bonding position (alignment/positioning), this taking place after the adhesive dispensing. In the bonding position the ECA blob is in contact not only with the PIC track but also an area on the connector pin surface. The adhesive is then held at an elevated temperature for a certain period of time to cure the adhesive, e.g. by heating the whole PIC/connector assembly in an oven (hot curing). Some ECAs may however cure at room temperature (cold curing) so do not require the adhesive to be heated to an elevated temperature. In the case of hot curing, the PIC/connector assembly is then cooled. In embodiments of the invention, the ECA may be either isotropic conductive adhesive (ICA) or anisotropic conductive adhesive (ACA).

DEVICE EXAMPLES

[0079] Some specific device examples are now described and illustrated by way of example. The same reference numerals are used as previously for corresponding parts.

[0080] Figure 12 is a schematic plan view of an example device configuration. The example device comprises a PIC 20 incorporating a high-frequency electro-optical modulator with a direct electrical connection to a coaxial connector 10. A module 50 accommodates the PIC 20 in which is integrated an electro-optical modulator based around a Mach-Zehnder interferometer. The PIC 20 is mounted on a suitable mounting board 56. The PIC 20 incorporates an optical source 21, such as a laser diode, and a network of waveguides 27 that form a Mach-Zehnder interferometer. The optical source 21 supplies light to the Mach-Zehnder interferometer via a waveguide 27. The PIC 20 has a CPW arranged on its surface with a signal track 24 and two ground tracks 22. The signal track 24 extends over one arm of the Mach-Zehnder interferometer so that an electrical signal, e.g. in the frequency range 50-110 GHz or 0-110 GHz, can effect phase modulation of the light travelling through that arm so that a digital signal can be impressed on the light emitted by the Mach-Zehnder interferometer. The light output from the Mach-Zehnder interferometer is supplied by a PIC waveguide 27 to an element 44 for coupling the PIC to an optical fibre 42 for onward transmission, e.g. to a long-haul optical fibre telecommunications line. An impedance matching circuit 40 is provided which is connected to both the signal and ground tracks 24, 22 of the CPW. The CPW signal and ground tracks 24, 22 of the PIC are electrically connected to an external cable via a coaxial connector 10 secured to a sidewall 54 of the module housing 52.

[0081] Figure 13 is a schematic plan view of another example device configuration. The device comprises a PIC 20 incorporating a high-bandwidth photodetector 25 with a direct electrical connection to a coaxial connector 10. A module 50 accommodates the PIC 20 in which is integrated a photodetector with a bandwidth of, for example, 50-110 GHz or 0-110 GHz. The PIC 20 is mounted on a suitable mounting board 56. A light signal to be detected is received into the module 50 by an optical fibre 42 which is coupled to the PIC 20 via a coupling element 44. The light signal is then conveyed within the PIC 20 by a waveguide 27 to the photodetector 25. The electrical signal from the photodetector 25 is then coupled out of the module via a coaxial connector 10 secured to a sidewall 54 of the module housing 52.

[0082] Figure 14 is a schematic plan view of a further example device configuration where the module is an optical transceiver. In this example, the PIC 20 incorporates both an electro-optical modulator acting as transmitter - as shown in Figure 12 - and a photodetector acting as receiver - as shown in Figure 13. The transmitter and receiver each have a direct electrical connection from the PIC 20 to their own coaxial connector 10.

REFERENCE NUMERALS

[0083]

- 5 blob of solder paste or ECA for signal connection
- 6 blob of solder paste or ECA for ground connections
- 10 coaxial connector**
- 12 coaxial connector, connector pin
- 14 coaxial connector, shell
- 16 coaxial connector, mounting flange
- 20 PIC, Photonic Integrated Circuit**
- 21 PIC optical source, e.g. laser diode
- 22 PIC CPW ground tracks
- 24 PIC CPW signal track
- 25 PIC photodiode
- 26 PIC substrate
- 27 PIC waveguide
- 28 PIC optical input
- 29 PIC optical output
- 30 EIC, Electronic Integrated Circuit (prior art only)**
- 32 EIC CPW ground tracks (prior art only)
- 34 EIC CPW signal track (prior art only)
- 36 EIC substrate (prior art only)
- 38 wire or ribbon bonding lines (prior art only)
- 40 impedance matching circuit
- 42 optical fibre
- 44 PIC-to-optical-fibre coupling element
- 50 module**

52 module housing
 54 module housing, sidewall
 55 module housing, sidewall aperture
 56 module, component mounting board
 5 **60 coaxial cable**
 62 core conductor, e.g. solid copper
 64 insulator, e.g. polyethylene
 66 conductive shield, e.g. copper braid or mesh
 68 outer insulating jacket, e.g. PVC

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[8] Instruction Sheet for the Anritsu W1-103F Connector (available at <https://dl.cdn-anritsu.com/en-us/test-measurement/files/Manuals/Instruction-Sheet/10305-0001PC.pdf>)

[9] US 6,543,677 (IBM)

[10] Kenneth Thum, Sze Pei Lim and KC Tai ULTRA-FINE SOLDER PASTE DISPENSING FOR HETEROGENEOUS INTEGRATION 2022 (available at <https://nswautomation.com/NSW/downloads-center/>).

Claims

1. A method of forming an electrical connection between a photonic integrated circuit and a coaxial connector, the method comprising:

providing a photonic integrated circuit having a planar transmission line that includes at least one track;
 providing a coaxial connector with a connector pin having an end length portion dimensioned and disposed in the coaxial connector to be suitable for bonding to the planar transmission line;
 dispensing onto an area of the track an amount of a solder paste or an electrically conductive adhesive to form a blob thereon; and, after said dispensing,
 moving the photonic integrated circuit relative to the coaxial connector to bring the end length portion of the connector pin into a bonding position in which the end length portion is in contact with the blob; and thereafter hardening the blob while the connector pin is held in the bonding position to form an electrical connection

between the connector pin and the track.

2. The method of claim 1, wherein the blob is a blob of solder paste.

3. The method of claim 2, further including heating to cause reflow of the solder blob before cooling to cause said hardening.

4. The method of claim 1, wherein the blob is a blob of electrically conductive adhesive.

5. The method of claim 4, further including heating to cure the electrically conductive adhesive blob before cooling to cause said hardening.

6. The method of any preceding claim, wherein in said bonding position an end length portion of the connector pin is in physical contact with the track.

7. The method of any preceding claim, wherein the track has a length portion with a width of less than one of: 400, 350, 300, 250, 200, 150, 130 and 100 micrometers defined by lateral edges thereof, and wherein the blob is formed on this length portion.

8. The method of claim 7, wherein the blob has a lateral extent that is confined so as not to extend beyond the lateral edges of the track.

9. The method of any preceding claim, wherein the end length portion of the connector pin has a maximum cross-sectional dimension equal to or less than one of: 300, 250, 200, 150, 130 and 100 micrometers.

10. A photonic integrated circuit that has been connected to a coaxial connector according to the method of any preceding claim.

11. A module containing a photonic integrated circuit, the module comprising:

a photonic integrated circuit comprising a planar transmission line that includes a track;
a coaxial connector with a connector pin; and
a blob of solder paste or electrically conductive adhesive in physical and electrically conductive contact with both an end length portion of the connector pin with a maximum cross-sectional dimension of equal to or less than 300 micrometres and a length portion of the track that has a width of equal to or less than 400 micrometers.

12. The module of claim 11, wherein the track on which the blob is formed has a further length portion with a further width that is less than said width, said length portion and said further length portion being interconnected by a tapered length portion of reducing width.

13. The module of claim 11 or 12, wherein the maximum cross-sectional dimension is equal to or less than one of: 250, 200, 150, 130 and 100 micrometres.

14. The module of claim 11, 12 or 13, wherein said length portion of the track accommodating the blob has a width of equal to or less than one of: 350, 300, 250, 200, 150, 130 and 100 micrometers.

15. Use of the module of any one of claims 11 to 14 to transmit a signal between the coplanar waveguide and the coaxial connector at a frequency greater than at least one of: 50 GHz, 67 GHz, 75 GHz, 100 GHz, 110 GHz and 145 GHz.

Amended claims in accordance with Rule 137(2) EPC.

1. A method of forming an electrical connection between a photonic integrated circuit and a coaxial connector, the method comprising:

providing a photonic integrated circuit (20, Figure 18C) having a planar transmission line (22, 24, Figure 18C) that includes at least one track;
providing a coaxial connector with a connector pin (12, Figure 18C) having an end length portion dimensioned

and disposed in the coaxial connector to be suitable for bonding to the planar transmission line;
 dispensing onto an area of the track an amount of a solder paste or an electrically conductive adhesive to form
 a blob (5, 6, Figure 18C) thereon; and, after said dispensing,
 moving the photonic integrated circuit relative to the coaxial connector to bring the end length portion of the
 connector pin into a bonding position in which the end length portion is in contact with the blob (Figure 18D);
 and thereafter
 hardening the blob while the connector pin is held in the bonding position to form an electrical connection
 between the connector pin and the track (Figure 19);
 obtaining an impedance-matched electrical response at the frequency of 75 GHz until 170 GHz, where the
 desired impedance has a deviation tolerance of $\pm 20\%$ across the frequency spectrum (Figure 20A and 20B
 serve as an example for the W-type connector).

2. The method of claim 1, wherein the blob is a blob of solder paste.

3. The method of claim 2, further including heating to cause reflow of the solder blob before cooling to cause said
 hardening.

4. The method of claim 1, wherein the blob is a blob of electrically conductive adhesive.

5. The method of claim 4, further including heating to cure the electrically conductive adhesive blob before cooling to
 cause said hardening.

6. The method of any preceding claim, wherein in said bonding position an end length portion of the connector pin is
 in physical contact with the track.

7. The method of any preceding claim, wherein the track has a length portion with a width of less than one of: 350,
 300, 250, 200, 150, 130 and 100 micrometers defined by lateral edges thereof, and wherein the blob is formed on
 this length portion.

8. The method of claim 7, wherein the blob has a lateral extent that is confined so as not to extend beyond the lateral
 edges of the track. The blob is confined to the width of the track after hardening.

9. The method of any preceding claim, wherein the end length portion of the connector pin has a maximum cross-
 sectional dimension equal to or less than one of: 300, 250, 200, 150, 130 and 100 micrometers.

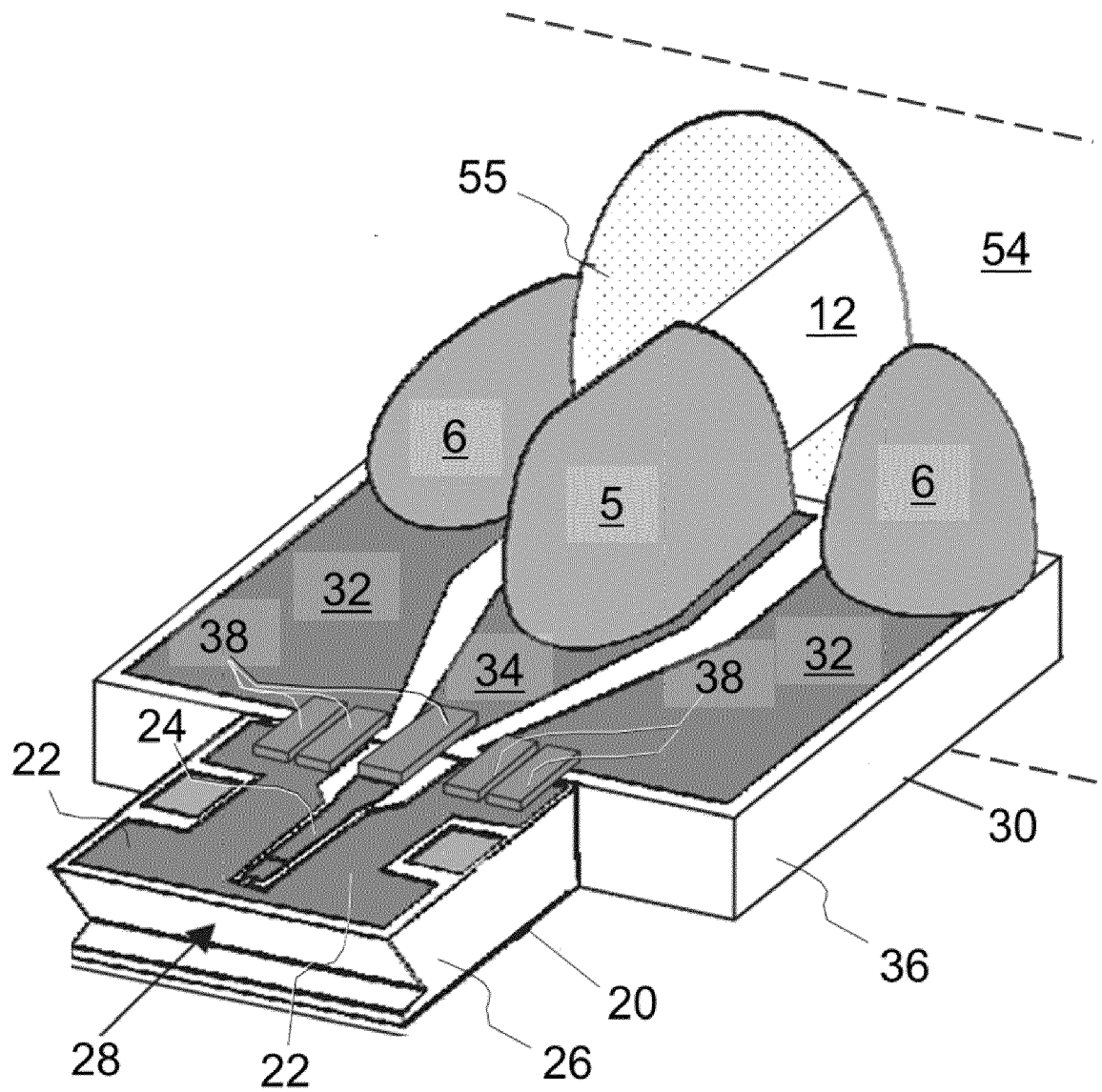
10. A photonic integrated circuit in an open, sealed or hermetic packaged module that has been connected to a coaxial
 connector according to the method of any preceding claim.

11. The module of claim 10, wherein the track on which the blob is formed has a further length portion with a further
 width that is less than said width, said length portion and said further length portion being interconnected by a tapered
 length portion of reducing width.

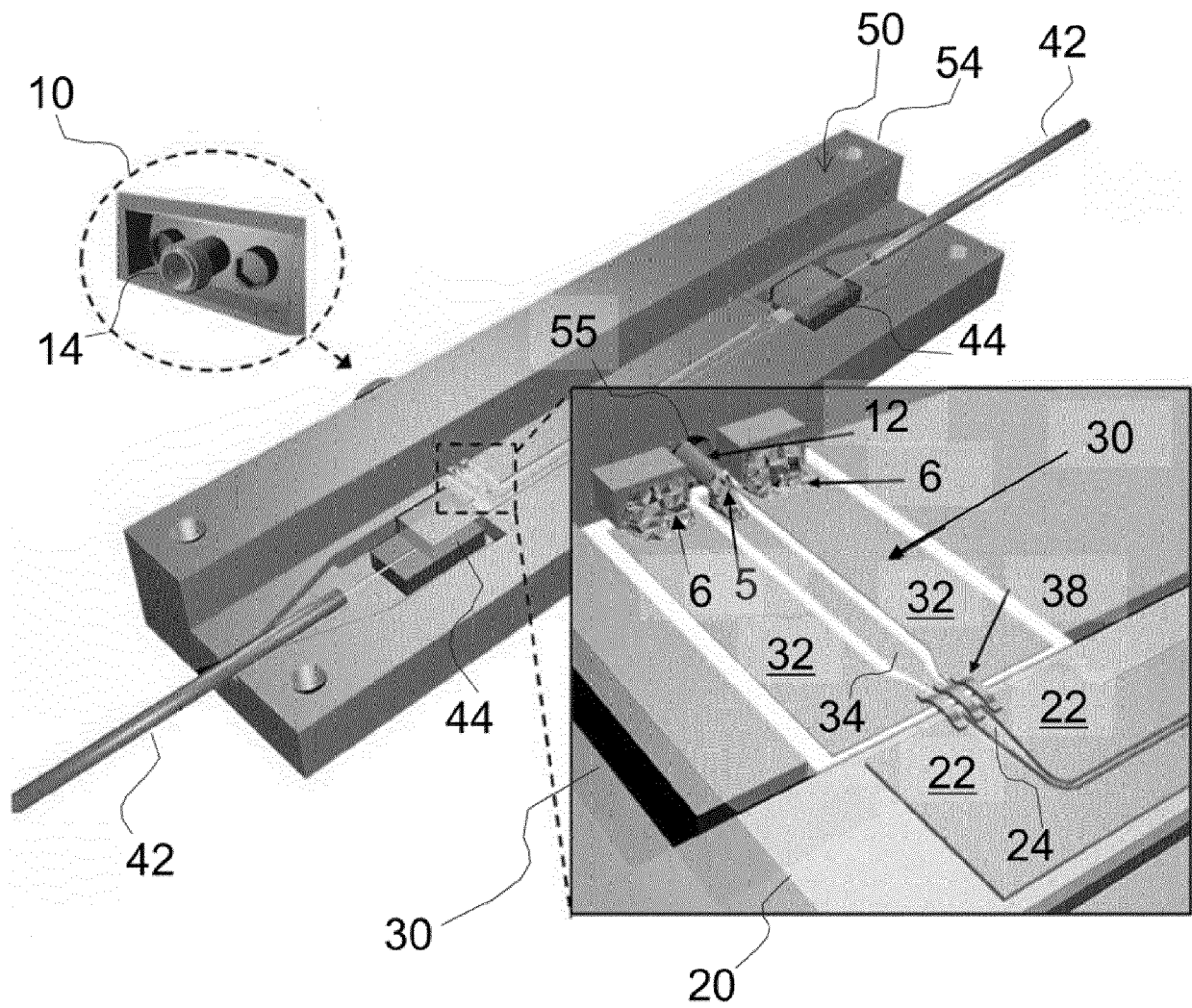
12. The module of claim 10 or 11, wherein the maximum cross-sectional dimension is equal to or less than one of: 250,
 200, 150, 130 and 100 micrometres.

13. The module of claim 10, 11 or 12, wherein said length portion of the track accommodating the blob has a width of
 equal to or less than one of: 350, 300, 250, 200, 150, 130 and 100 micrometers.

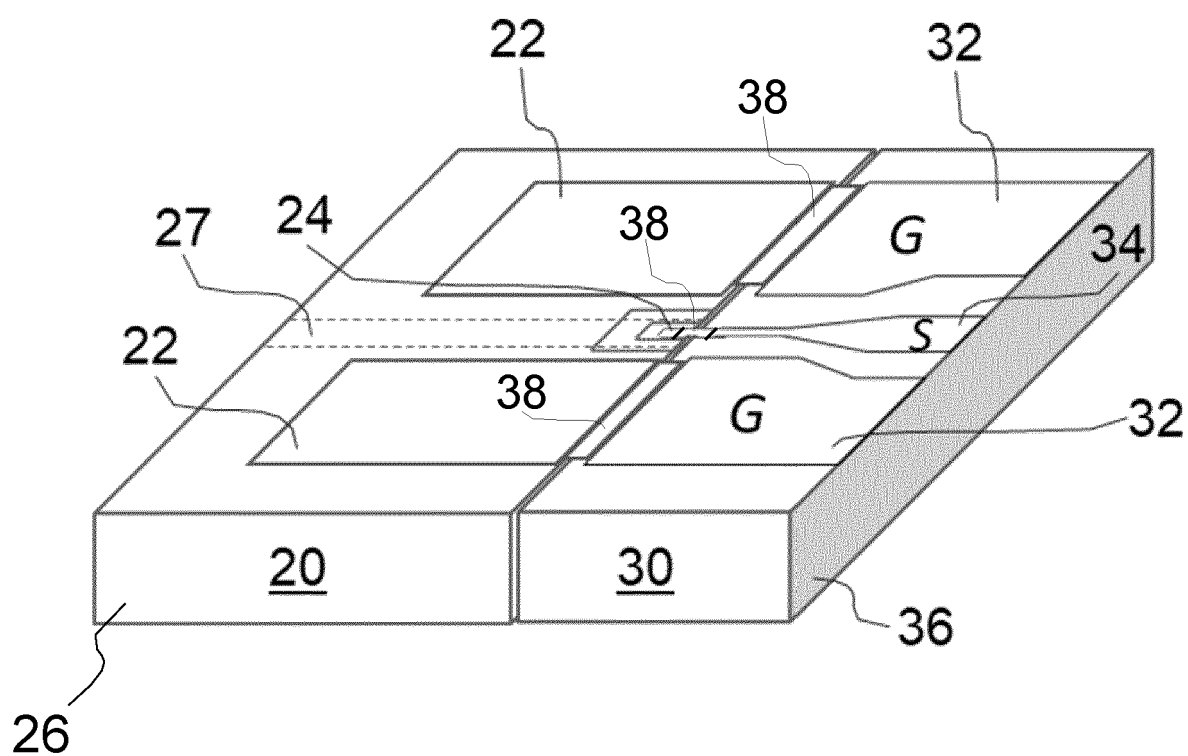
14. Use of the module of any one of claims 10 to 13 to transmit an impedance-matched signal between the coplanar
 waveguide and the coaxial connector at a frequency greater than at least one of: 75 GHz, 100 GHz, 110 GHz and
 145 GHz.



PRIOR ART
FIG. 1



PRIOR ART
FIG. 2



PRIOR ART
FIG. 3

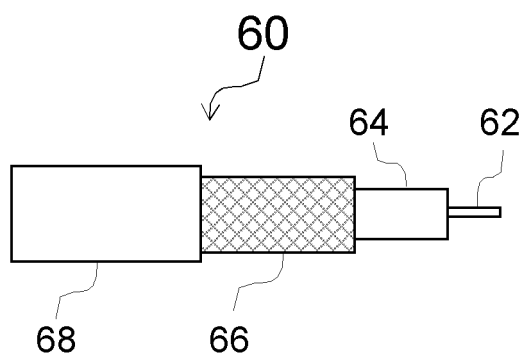


FIG. 4

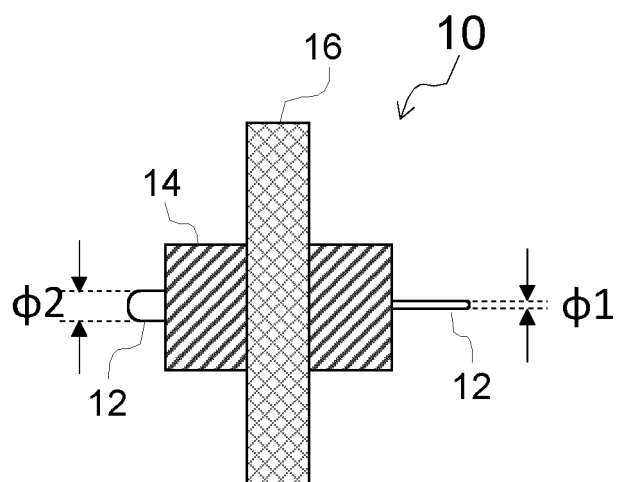


FIG. 5

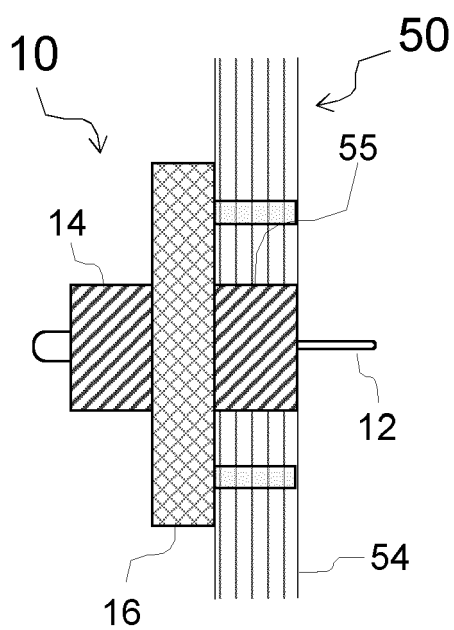


FIG. 6A

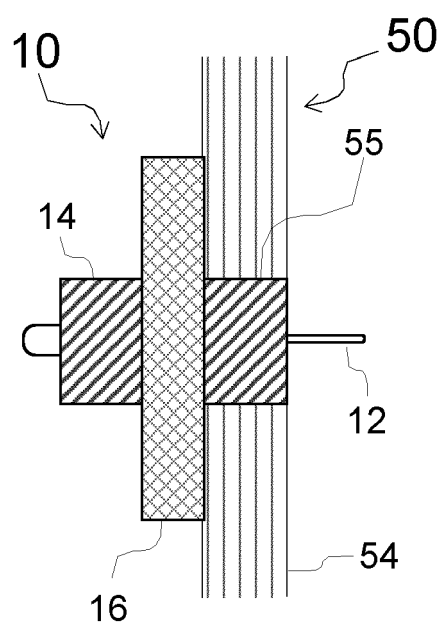


FIG. 6B

FIG. 7A

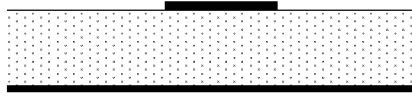


FIG. 7B

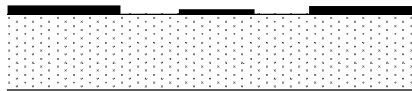


FIG. 7C

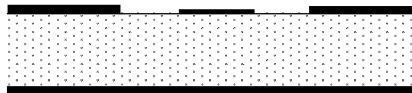


FIG. 7D

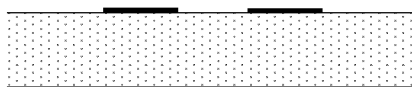


FIG. 7E

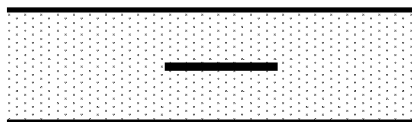
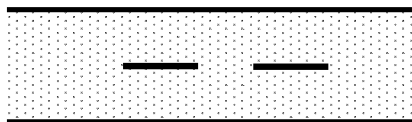


FIG. 7F



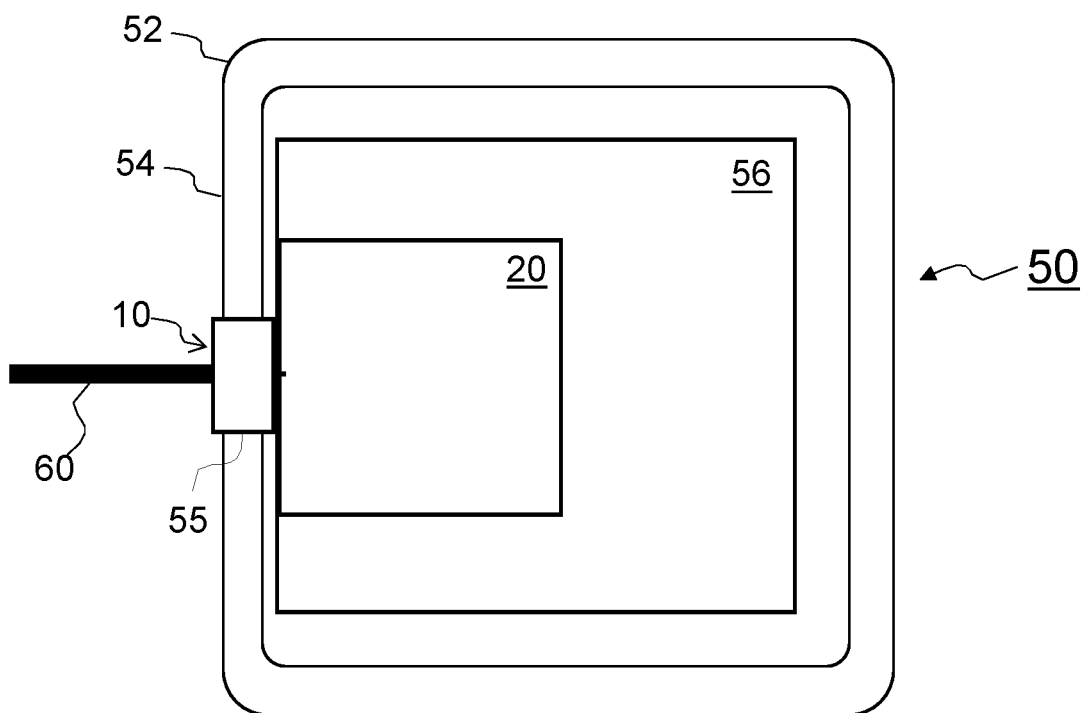


FIG. 8

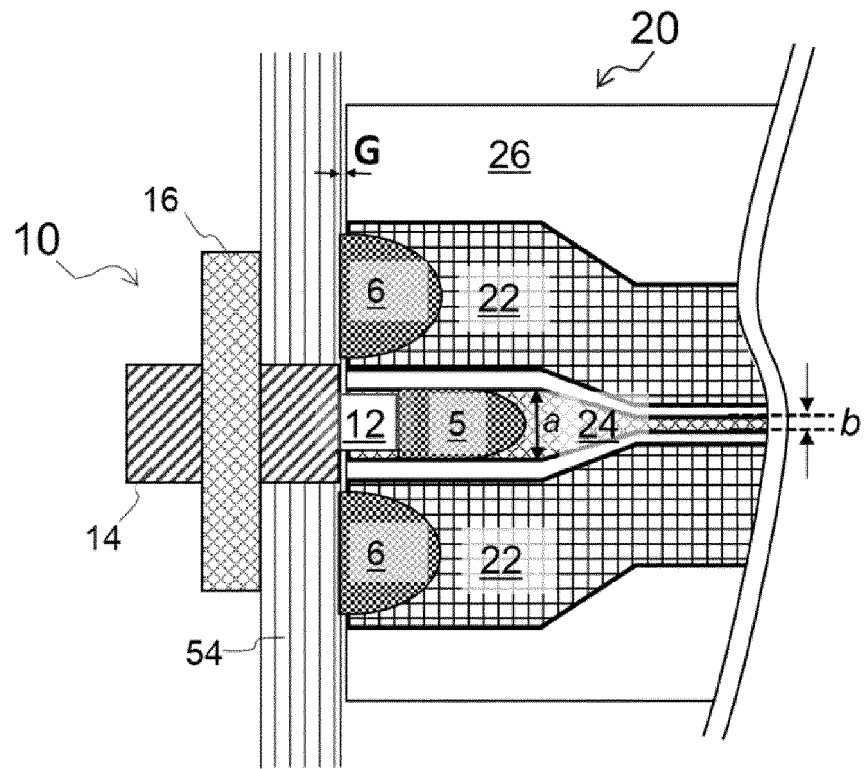


FIG. 9

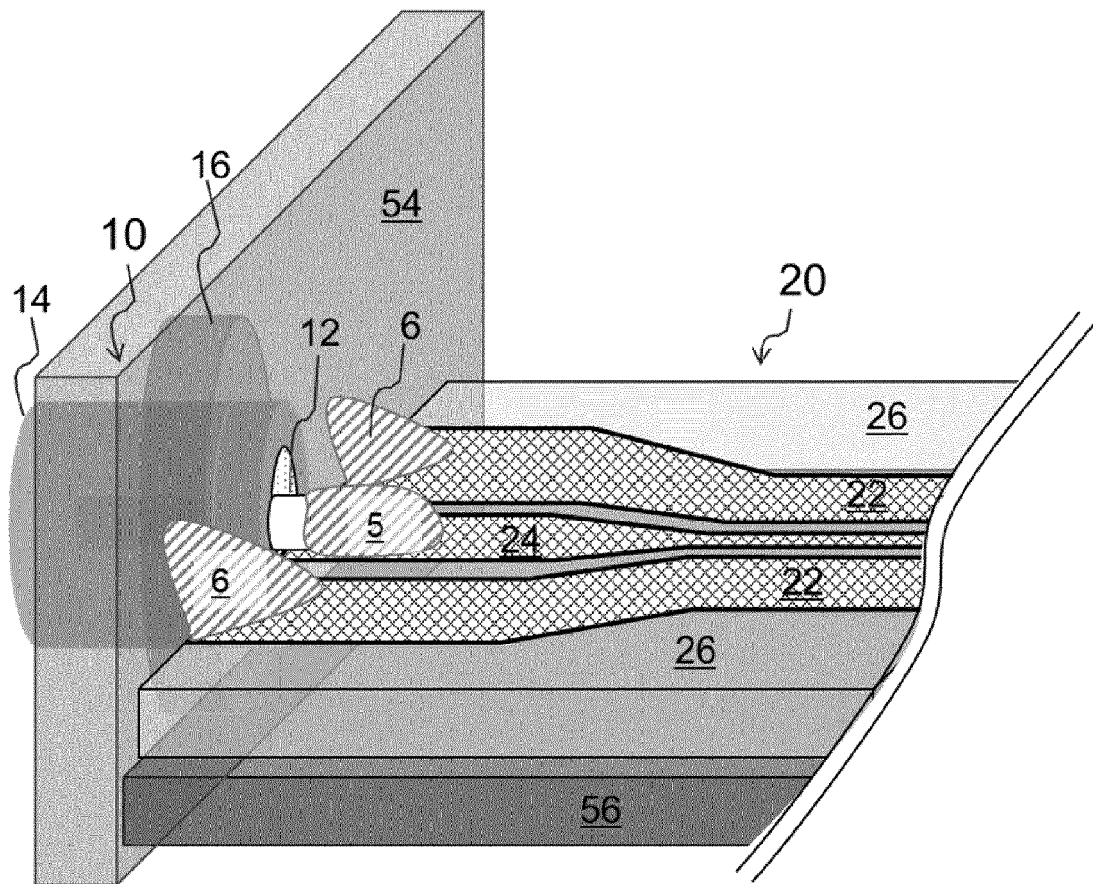


FIG. 10

FIG. 11A

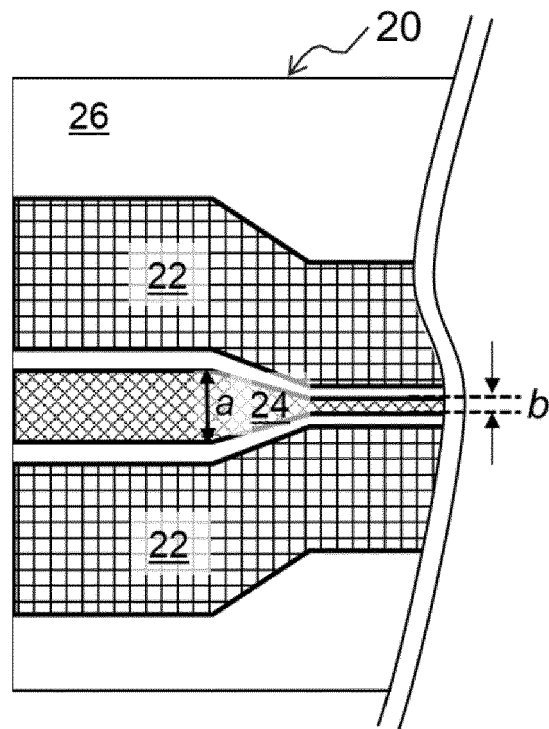
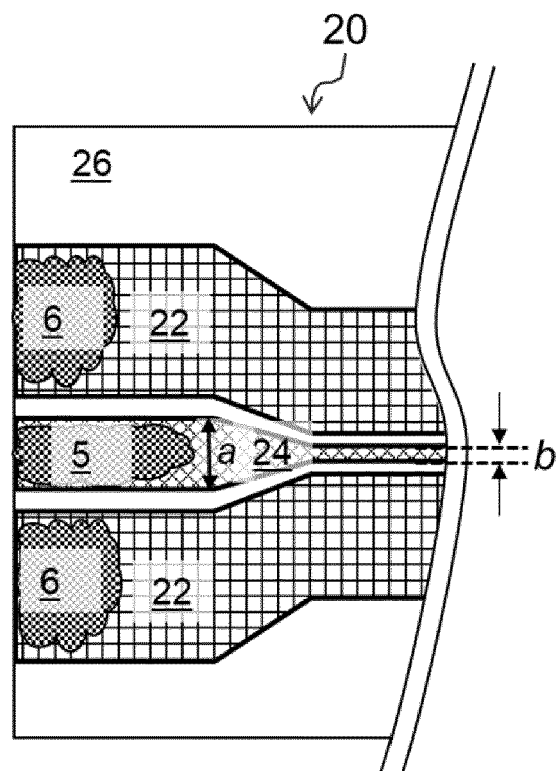


FIG. 11B



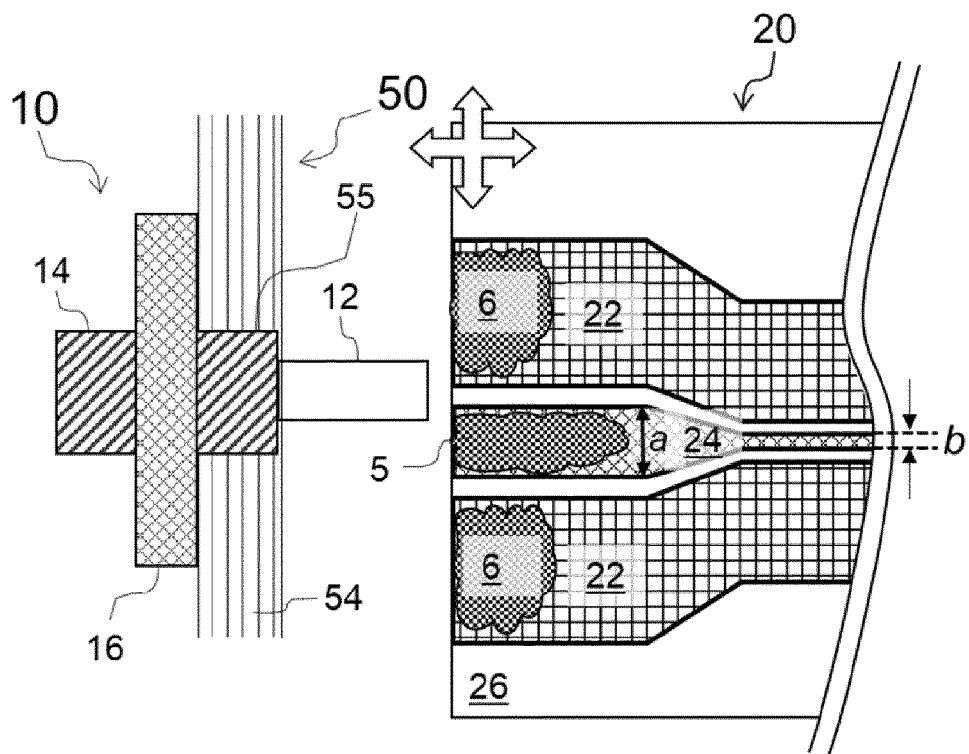


FIG. 11C

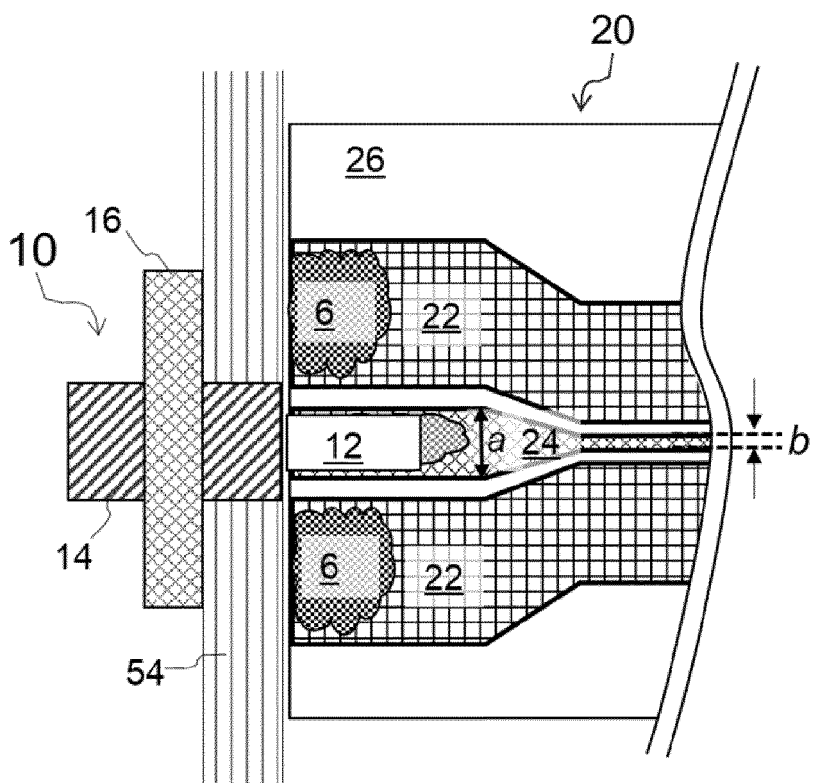


FIG. 11D

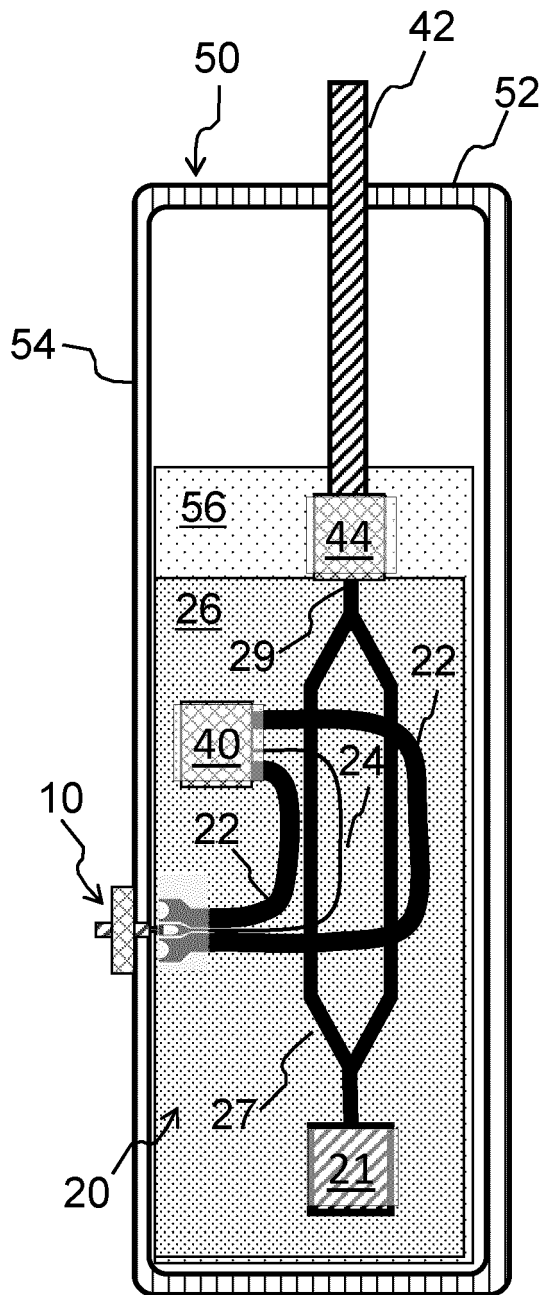


FIG. 12

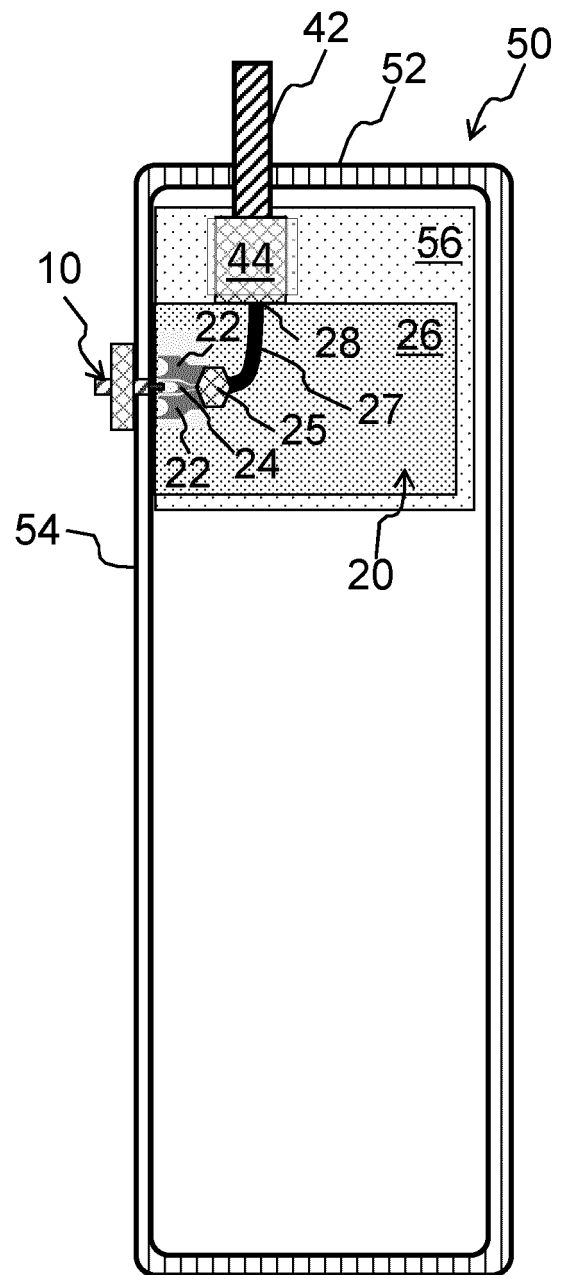


FIG. 13

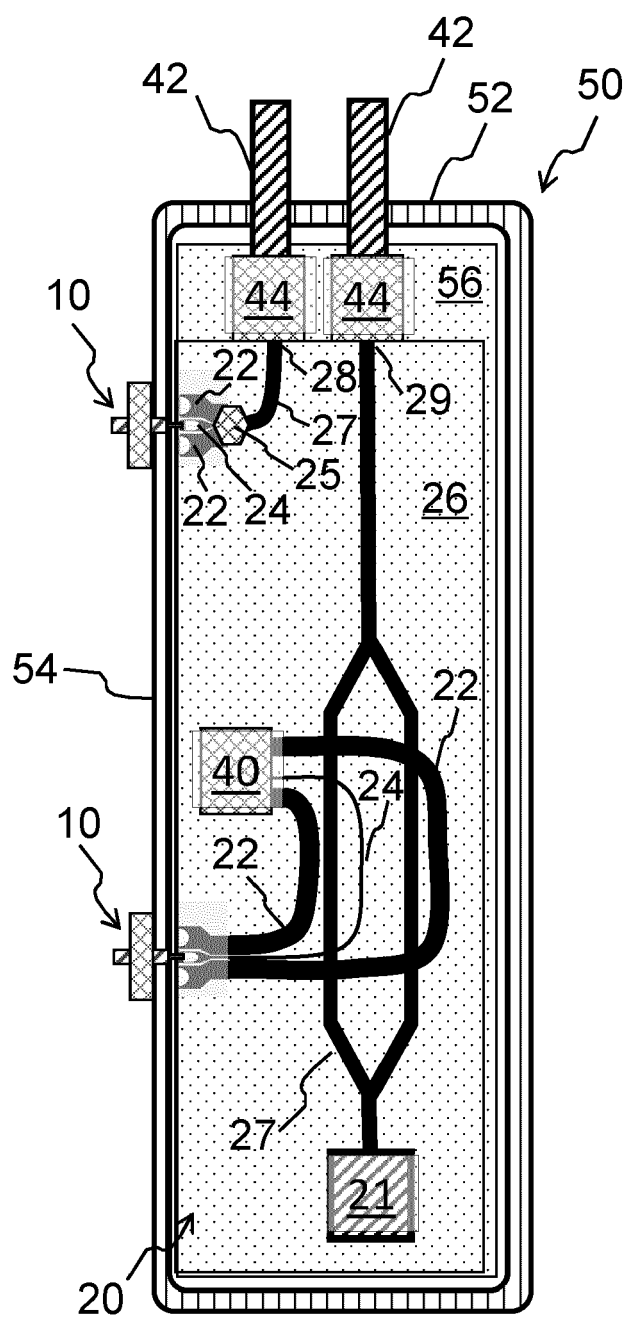


FIG. 14



EUROPEAN SEARCH REPORT

Application Number

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DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	GRANT PETER D. ET AL: "Ultrafast quantum well infrared photo detector", LASER-BASED MICRO- AND NANOPACKAGING AND ASSEMBLY II, vol. 5578, 9 December 2004 (2004-12-09), pages 309-314, XP093099144, ISSN: 0277-786X, DOI: 10.1117/12.567260 * sections 2. and 3.; page 310 - page 312; figures 1, 2 * & Anritsu: "Anritsu Microwave V Connector", , 1 November 2012 (2012-11-01), pages 1-1, XP093099182, Retrieved from the Internet: URL:https://dl.cdn-anritsu.com/en-us/test-measurement/files/Manuals/Instruction-Sheet/10100-00047B.pdf [retrieved on 2023-11-08] * pages 5-1; tables 5-1 * & Advanced Technology Group: "V-Glass Bead", , 1 April 1999 (1999-04-01), pages 1-1, XP093099173, Retrieved from the Internet: URL:https://advtechgr.com/wp-content/uploads/ATG_V100_TechnicalSpecifications.pdf [retrieved on 2023-11-08] * page 1 * -/--	1-15	INV. H01P5/08 H01R9/05 H01R24/40 TECHNICAL FIELDS SEARCHED (IPC) H01P H01R H01L G02B
The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 1 December 2023	Examiner Blech, Marcel
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 1 December 2023	Examiner Blech, Marcel
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons ----- & : member of the same patent family, corresponding document	



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Application Number

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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The present search report has been drawn up for all claims			TECHNICAL FIELDS SEARCHED (IPC)
Place of search The Hague			Date of completion of the search 1 December 2023
Examiner Blech, Marcel			
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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15	US 7625131	B2	01-12-2009	NONE
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