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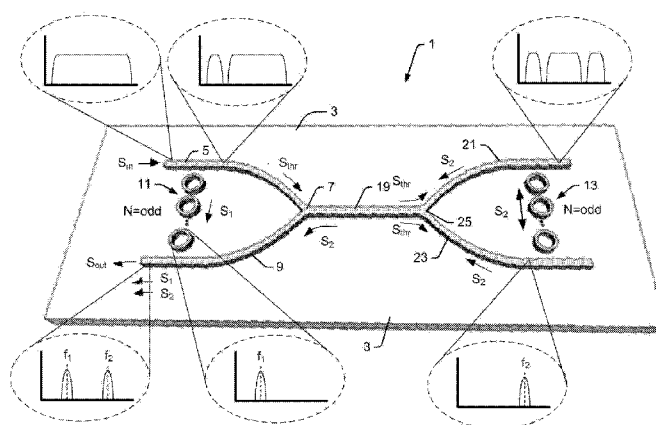


Figure 1

(57) Abstract: Described herein is a dual band optical filter (1) including an input waveguide (5) to input an optical signal (S_{in}) and an output waveguide (9) to output a filtered optical signal (S_{out}). A first filter path is disposed between the input waveguide (5) and the output waveguide (9) and is configured to couple a first frequency component (f_1) of the optical signal (S_{in}) to the output waveguide (9) as a first band (S_1) of the filtered optical signal (S_{out}). A second filter path is disposed between the input waveguide (5) and the output waveguide (9) and is configured to couple a second frequency component (f_2) of the optical signal (S_{in}) to the output waveguide (9) to form a second band (S_2) of the filtered optical signal (S_{out}). Also described is the use of optical ring resonator arrangements to provide filtering of the optical signal (S_{in}) in each filter path.



DUAL BAND OPTICAL FILTER AND PHOTONIC RECEIVER BASED THEREON

FIELD OF THE INVENTION

[0001] The present invention relates to photonic radio frequency (RF) filtering and in particular to a dual band optical filter and a photonic receiver based thereon. While some embodiments will be described herein with particular reference to that application, it will be appreciated that the invention is not limited to such a field of use, and is applicable in broader contexts.

BACKGROUND

[0002] Any discussion of the background art throughout the specification should in no way be considered as an admission that such art is widely known or forms part of common general knowledge in the field.

[0003] One of the fundamental problems with discrete time signal processors is that the filter transfer function is periodic, having multiple harmonic passbands with a period given by the free spectral range (FSR). This is a generic phenomenon that intrinsically occurs in all discrete time signal processors because of the discrete nature of the sampling process in the time domain (see J. Capmany *et al.*, Journal of Light. Tech. 31 (2013) p.571 and R.A. Minasian *et al.*, Opt.Express 21 (2013) p. 22918). The harmonic passband presents a serious drawback because it restricts the processing frequency to a fraction of the FSR in order to avoid spectral overlapping. For wideband operation it is important to realize microwave photonic filters that have a single bandpass without a baseband response, which are free from multiple periodic spectral responses.

[0004] Moreover, the field of electronic signal detection requires powerful signal pre-processing tools to recognize and classify detected signals. Microwave photonic receivers are of particular interest due to their ability to report the existence of detected signals and perform instantaneous spectrum activity monitoring (see [4] A. A. Savchenkov *et al.*, IEEE Transactions on Microwave Theory and Techniques, 58 (2010) p.3167). Recently, various photonic-assisted channelization approaches have been presented including parametric mixing, coherent optical frequency combs and stimulated Brillouin scattering. These schemes are based on the usage of multiple light sources, which increases the system complexity and cost.

[0005] The usage of high selective optical filters in microwave photonic signal processing is an effective approach to achieve single passband RF filtering, frequency recognition and single sideband electro-optical modulator. Signal processing using silicon ring resonators is of great interest due to their compact size as well as compatibility with complementary metal-oxide semiconductor (CMOS) fabrication techniques. Conventional ring resonator based optical filters are designed to have only one single passband to select the modulated signal while the carrier signal is either completely neglected or added back to the filtered signal via additional couplers. The former is not favoured as precise frequency and phase information of the RF signal will be lost, while the latter presents the problem of increased insertion loss as well as degradation of the carrier signal due to the extra couplers. Moreover, as wide operating range is of importance for channelized receivers, a large number of couplers are needed, rendering the whole device bulky and imposing stringent requirements on fabrication.

[0006] Thus, there is a desire for improved or alternative channelized optical receivers.

SUMMARY OF THE INVENTION

[0007] It is an object of the invention, in its preferred form to provide an improved or alternative dual band optical filter and optical receiver.

[0008] In accordance with a first aspect of the present invention there is provided a dual band optical filter including:

- an input waveguide to input an optical signal;

- an output waveguide to output a filtered optical signal;

- a first filter path disposed between the input waveguide and the output waveguide and configured to couple a first frequency component of the optical signal to the output waveguide as a first band of the filtered optical signal; and

- a second filter path disposed between the input waveguide and the output waveguide and configured to couple a second frequency component of the optical signal to the output waveguide to form a second band of the filtered optical signal.

[0009] In one embodiment, the first filter path includes a first ring resonator arrangement coupled at a first end to the input waveguide and at a second end to the output waveguide, the first ring resonator arrangement including at least one optical ring resonator configured to couple the first frequency component of the optical signal from the input waveguide to the output waveguide.

[0010] In one embodiment, the second filter path includes a second ring resonator arrangement, the second ring resonator arrangement including at least one optical ring resonator configured to couple the second frequency component of the optical signal from the input waveguide to the output waveguide.

[0011] In one embodiment, the input waveguide and the output waveguide are connected to define first and second arms of a first 'Y' shaped waveguide junction, a third arm of the first 'Y' shaped waveguide junction defining a bidirectional waveguide that is coupled to the second ring resonator arrangement.

[0012] In one embodiment, the bidirectional waveguide defines a first arm of a second 'Y' shaped waveguide junction, a second arm of the second 'Y' shaped waveguide junction being coupled to a first end of the second ring resonator arrangement and a third arm of the second 'Y' shaped waveguide junction being coupled to a second end of the second ring resonator arrangement, the bidirectional waveguide being configured to couple the optical signal from the first 'Y' shaped waveguide junction to the second 'Y' shaped waveguide junction and to couple the second frequency component from the second ring resonator arrangement to the first 'Y' shaped waveguide junction.

[0013] In one embodiment, the bidirectional waveguide is coupled directly to the second ring resonator arrangement.

[0014] In one embodiment, a first end of the second ring resonator arrangement is coupled to the bidirectional waveguide and a second end of the second ring resonator arrangement is coupled to a reflective waveguide structure configured to reflect the second frequency component through a second pass of the second ring resonator arrangement and back to the bidirectional waveguide.

[0015] In one embodiment, the waveguide reflector is a Bragg grating. In another embodiment, the waveguide reflector is a loop mirror.

[0016] In one embodiment, the second ring resonator arrangement includes a plurality of optical ring resonators disposed in a coupled array extending parallel to a coupling waveguide in a side-coupled integrated spaced sequence of resonators (SCISSOR) arrangement.

[0017] In one embodiment, the bidirectional waveguide is coupled to a loop waveguide and wherein the second ring resonator arrangement is disposed along the loop and includes a plurality of optical ring resonators disposed along a portion of the loop waveguide in a coupled array and extending parallel to a coupling waveguide in a side-coupled integrated spaced sequence of resonators (SCISSOR) arrangement.

[0018] In one embodiment, the first ring resonator arrangement includes a plurality of coupled optical ring resonators. Preferably, the first ring resonator arrangement includes an odd number of coupled optical ring resonators disposed in an optical chain. In preferred embodiments, the first ring resonator arrangement includes three coupled optical ring resonators disposed in an optical chain.

[0019] In one embodiment, the second ring resonator arrangement includes a plurality of coupled optical ring resonators disposed in an optical chain. Preferably, the second ring resonator arrangement includes an even number of optical ring resonators disposed in an optical chain. In one embodiment, the second ring resonator arrangement includes two coupled optical ring resonators.

[0020] In one embodiment, the second filter path includes second and third ring resonator arrangements, the second and third ring resonator arrangements being disposed at respective bends along the second filter path and each including an even number of optical ring resonators configured to couple the second frequency component of the optical signal from the input waveguide to the output waveguide.

[0021] In one embodiment, the first ring resonator arrangement includes a plurality of optical ring resonators disposed in a coupled array extending parallel to a coupling waveguide in a side-coupled integrated spaced sequence of resonators (SCISSOR) arrangement.

[0022] Preferably, the dual band optical filter is formed on a photonic chip.

[0023] In accordance with a second aspect of the present invention there is provided a photonic receiver including:

- an optical source to provide an optical carrier signal;

- an input for receiving an electromagnetic signal to be analysed;

- an electro-optic modulator to modulate the optical carrier signal with the electromagnetic signal so as to generate a modulated optical signal;

- one or more dual band optical filters according to any one of the preceding claims, each configured to receive the modulated signal and output a dual band filtered modulated signal; and

- one or more photodetectors configured to detect the dual band filtered modulated signal.

[0024] Preferably, the first band is centred around a carrier frequency (f_c) of the optical carrier signal. Preferably, the second band is centred around a frequency equal to $f_c + f_i$, where f_i is a frequency of the input signal to be analysed.

[0025] In one embodiment, the receiver includes a power splitter disposed intermediate the optical modulator and the one or more dual band optical filters, the power splitter configured to split the optical power of the modulated signal equally between each of the one or more dual band optical filters.

[0026] Preferably, the receiver is formed on a photonic chip.

[0027] In accordance with a third aspect of the present invention there is provided a photonic receiver including:

- a narrowband optical light source for emitting a first optical signal;

- a first optical modulator modulating the first optical signal in accordance with an externally received electromagnetic signal so as to produce a modulated optical signal;

- a series of optical resonator structures coupled to the modulated optical signal and outputting at least an optical sideband signal from the modulated optical signal.

[0028] In one embodiment, each of the optical resonator structures include:

- a first coupled resonator optical waveguide interconnected to a second coupled resonator optical waveguide to separate the sideband signal and modulated optical signal.

[0029] Preferably, the optical ring resonator structures output a series of pass band signals.

[0030] Preferably, the first coupled resonator optical waveguides include optical ring resonators.

[0031] Preferably, a plurality of sideband signals are output from the optical resonator structures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0032] Preferred embodiments of the disclosure will now be described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 is a schematic plan view of a dual band optical filter according to a first embodiment of a first aspect of the invention illustrating snapshots of optical spectra at different locations within the filter;

Figure 2 is a plan view of a first ring resonator arrangement within the optical filter of Figure 1;

Figure 3 is a schematic plan view of a dual band optical filter according to a second embodiment of the invention;

Figure 4 is a schematic plan view of a dual band optical filter according to a third embodiment of the invention;

Figure 5 is a schematic plan view of a dual band optical filter according to a fourth embodiment of the invention;

Figure 6 is a schematic plan view of the dual band optical filter of Figure 5 wherein the optical reflector is represented as a micro-loop mirror;

Figure 7 is a plan view microscopy image of the fabricated dual band optical filter device of Figure 5;

Figure 8 a schematic plan view of a dual band optical filter according to a fifth embodiment of the invention;

Figure 9 is a schematic plan view of a dual band optical filter according to a sixth embodiment of the invention;

Figure 10 is a schematic plan view of a dual band optical filter according to a seventh embodiment of the invention;

Figure 11 is a schematic plan view of a dual band optical filter according to an eighth embodiment of the invention;

Figure 12 is a schematic plan view of a dual band optical filter according to a ninth embodiment of the invention;

Figure 13 is a schematic plan view of a dual band optical filter according to a tenth embodiment of the invention;

Figure 14 is a schematic functional view of an optical receiver according to a second aspect of the present invention;

Figure 15 is a graph of eight simulated channel responses of dual band optical filters as generated in the MATLABTM software;

Figure 16 is a first graph of simulated results of three RF frequency signals modulated with a 194.987 THz optical carrier signal as generated in the VPITransmissionMaker™ software, the graph illustrating the detection of a first of the RF frequency signals;

Figure 17 is a second graph of simulated results of three RF frequency signals modulated with a 194.987 THz optical carrier signal as generated in the VPITransmissionMaker™ software, the graph illustrating the detection of a second of the RF frequency signals; and

Figure 18 is a third graph of simulated results of three RF frequency signals modulated with a 194.987 THz optical carrier signal as generated in the VPITransmissionMaker™ software, the graph illustrating the detection of a third of the RF frequency signals.

DETAILED DESCRIPTION

[0033] Referring to Figure 1 there is illustrated a dual band optical filter 1 formed on a photonic chip substrate 3 such as a complementary metal-oxide semiconductor (CMOS) chip. Filter 1 includes an input optical waveguide 5 to input an optical signal (S_{in}) in the form of an optical beam from a coupled optical source (not shown). The input waveguide 5 and other waveguides described herein are preferably formed from optical fibers. However, in some embodiments, waveguides may be physically defined in the substrate 3 through techniques such as etching and deposition. Input waveguide 5 has a curved longitudinal profile and interconnects with two other waveguides in a 'Y' shaped junction 7. A first of the waveguides interconnected with the input waveguide 5 is an output waveguide 9. Output waveguide 9 is curved in an equal but opposite manner to that of input waveguide 5 and is positioned to output a filtered optical signal (S_{out}) from the optical filter 1. Each of the waveguides in filter 1 has cross-sectional dimensions so as to support predetermined electromagnetic modes over a predetermined range of supported wavelengths. Exemplary waveguide structures include optical fibres, silica and silicon nitride based waveguides and silicon-on-insulator (SOI) waveguides. It will be appreciated that the curvature of the various waveguides is flexible in design and is generally selected to more efficiently utilise the space available on substrate 3 while supporting the required waveguide mode propagation. Thus, waveguides illustrated as being straight may be curved and vice versa.

[0034] Filter 1 includes first and second ring resonator arrangements 11 and 13 formed from optical fibers that have respective resonant structures for selecting first and second

frequency components from the input optical signal. First ring resonator arrangement 11 is coupled at a first end to input waveguide 5 and, at a second end, to output waveguide 9. First ring resonator arrangement 11 preferably includes three optical ring resonators arranged in a linear coupled optical chain, as illustrated in Figure 2. Each ring resonator is substantially identical in diameter. The diameter is selected to define a path length that supports a first filtered optical signal (S_1) having a first frequency band (f_1).

[0035] With reference to Figure 2, the operation of first ring resonator arrangement 11 will now be described. Coupling of optical radiation to an optical ring resonator occurs when the wavelength of radiation matches the resonance condition of the ring. That is, when the ring diameter is equal to an integer number of wavelengths of the radiation such that constructive interference occurs. In practice, a small range or band of frequencies are supported at resonance with a central frequency (or wavelength) corresponding to the maximum efficiency coupling. This small band of frequencies represents the first frequency band f_1 .

[0036] Upon propagation along input waveguide 5, some radiation of the signal couples into the first ring resonator 15 due to its close proximity to input waveguide 5. The strength of the coupling is determined by the distance between ring resonator 15 and input waveguide 5. A larger distance results in a weaker coupling of radiation. The specific diameter of ring resonator 15 supports frequency band f_1 in the resonance condition and couples this band efficiently to the ring to define signal S_1 . Different diameter rings have different resonance conditions and support different frequency bands. Successive passes around ring resonator 15 result in constructive interference and the radiation intensity builds up inside the ring.

[0037] During the coupling, the flow of optical energy is conserved and propagation of radiation within a ring is determined by the direction of propagation before coupling. Given that the input signal is propagating to the right through input waveguide 5, propagation of the first filtered optical signal S_1 within ring resonator 15 is in the clockwise direction as illustrated. As the radiation intensity within ring resonator 15 builds up, radiation couples to second ring resonator 16 in a similar manner to the coupling between input waveguide 5 and first ring resonator 15. Propagation of signal S_1 within this second ring resonator 16 is in the counter clockwise direction. A similar coupling process again occurs from second ring resonator 16 into third ring resonator 17 with propagation of signal S_1 in the third ring in the clockwise direction.

[0038] Given that the diameters of each of the rings are substantially identical (to within permitted performance or tolerance levels) the same frequency band f_1 is supported through each ring. However, the propagation through the three rings essentially acts like a triple-pass of an optical filter and each ring acts to sharpen or steepen the edges of the overall profile of the passed frequency band f_1 of signal S_1 . Finally, due to close proximity between third ring resonator 17 and output waveguide 9, signal S_1 is coupled to output waveguide 9 in a propagation direction to the left in Figure 2. Thus, first ring resonator arrangement 11 defines a first optical filter path for coupling first filtered optical signal S_1 from input waveguide 5 to output waveguide 9.

[0039] Through the above described operation, it will be appreciated that first ring resonator arrangement 11 can include any odd number of ring resonators to achieve the desired filtering or frequency selectivity. Thus, in other embodiments, first ring resonator arrangement 11 includes 1, 5, 7, 9 or a greater odd number of ring resonators. Generally, a greater number of rings produces a frequency band with steeper rolloff but this comes at the expense of additional system complexity, optical loss and cost. Thus, an arrangement of 3 coupled ring resonators provides good balance between frequency selectivity, system complexity/cost and optical loss.

[0040] Returning to Figure 1, a bidirectional waveguide 19 is interconnected at a first end to both input waveguide 5 and output waveguide 9 at junction 7 to complete the 'Y' structure. Thus junction 7 is defined by the connection of the three waveguides 5, 9 and 19. At a second end, bidirectional waveguide 19 interconnects with an upper curved waveguide 21 and a lower curved waveguide 23 to form a second 'Y' shaped waveguide junction 25. Thus, as illustrated in Figure 1, the whole waveguide structure of dual band optical filter 1 is symmetrical in shape about a centre of bidirectional waveguide 19.

[0041] The frequencies of the input optical signal not coupled through first ring resonator arrangement 11 propagate from input waveguide 5, through junction 7 and couple into the bidirectional waveguide 19. This portion of the signal is designated ' S_{thr} ' in Figure 1 indicating a 'through' signal. The S_{thr} signal is coupled from the bidirectional waveguide 19 into both the upper 21 and lower 23 curved waveguides respectively.

[0042] Second ring resonator arrangement 13 is disposed between upper curved waveguide 21 and lower curved waveguide 23. Second ring resonator arrangement 13 preferably includes three optical ring resonators disposed in a linear coupled optical chain similar to that of first ring resonator arrangement 11. The diameters of each ring in second ring resonator arrangement 13 are substantially identical to each other (to within permitted performance or tolerance levels) but are different in diameter to those of first ring

resonator arrangement 11 so as to select a second frequency band f_2 for coupling to define a second filtered optical signal S_2 . Frequency band f_2 may be at higher or lower frequencies than frequency band f_1 depending upon parameters of the optical ring resonators in ring resonator arrangements 11 and 13. As S_{thr} propagates through arrangement 13 in both directions, signal S_2 is filtered from S_{thr} in a similar manner to that described above in relation to first ring resonator arrangement 11 (and illustrated in Figure 2), and is returned along both upper 21 and lower 23 curved waveguides.

[0043] Signal S_2 propagates back along bidirectional waveguide 19 and is coupled into output waveguide 9 and output together with signal S_1 to form S_{out} . Snapshots of the spectra at different points in filter 1 are illustrated in Figure 1. As shown, two discrete narrowband signals representing bands f_1 and f_2 are output as S_{out} at output waveguide 9. Propagation of the remaining undesired frequencies of input signal S_{in} are attenuated by appropriate waveguide attenuators.

[0044] In filter 1 of Figure 1, second ring resonator arrangement 13 is connected indirectly to both input waveguide 5 and output waveguide 9 through bidirectional waveguide 19. Thus, the propagation of signal S_2 from input waveguide 5, through bidirectional waveguide 19, second ring resonator arrangement 13 and output waveguide 9 represents a second optical filter path.

[0045] Referring to Figure 3, there is illustrated a second embodiment dual band optical filter 27 wherein ring resonator arrangements 11 and 13 are connected in parallel between input waveguide 5 and output waveguide 9. In this embodiment, the Y junctions and bidirectional waveguide are omitted.

[0046] A number of other alternative embodiments of the optical filter are described below. Each of these embodiments provide efficient dual band optical output without the need for an optical circulator. In the various embodiments described below, corresponding features of filter 1 are designated with the same reference numerals.

[0047] Referring now to Figure 4, there is illustrated a third embodiment dual band optical filter 30 including a similar structure to filter 1 of Figure 1. The primary difference over filter 1 is that second ring resonator arrangement 13 of filter 30 includes an even number of ring resonators. This results in the second signal S_2 propagating to the right upon coupling from second ring resonator arrangement 13. To account for the right hand propagation of this signal, an extra 'U' shaped waveguide 32 is utilised to couple the frequency band to lower curved waveguide 23 and subsequently to output waveguide 9.

Otherwise, the operation of filter 30 is substantially similar to that of dual band optical filter 1.

[0048] Referring now to Figure 5, there is illustrated a fourth embodiment dual band optical filter 34. In filter 34, first ring resonator arrangement 11 is disposed in the same position between input waveguide 5 and output waveguide 9 as with previous embodiments. A second end of bidirectional waveguide 19 is in a direct resonant coupling with a first end of second resonator arrangement 13. Second ring resonator arrangement 13 includes an even number of optical ring resonators arranged in a linear coupled optical chain and preferably includes 2 rings. As with previous embodiments, the diameters of the optical ring resonators of second ring resonator arrangement 13 are such that they resonantly support the second frequency band f_2 . A second end of arrangement 13 is positioned to couple the second filtered optical signal S_2 to a coupling waveguide 36. Given that second ring resonator arrangement 13 includes an even number of optical ring resonators, the propagation of signal S_2 in waveguide 36 is in a direction to the right in Figure 5. The right hand end of coupling waveguide 36 is coupled to an optical reflector 38 that is configured to reflect signal S_2 back along waveguide 38 and through a second pass of arrangement 13. Optical reflector 38 may be one of a number of different devices, including a reflective Bragg reflector, reflective etalon, Sagnac loop mirror or other type of optically reflective device. Figure 6 illustrates an exemplary dual band optical filter 40 wherein the reflector is a micro-loop mirror 42.

[0049] Signal S_2 is then coupled back to bidirectional waveguide 19 and then to output waveguide 9 and output together with signal S_1 to form output signal S_{out} . As with other embodiments, the remaining signal S_{thr} that lies outside of bands f_1 and f_2 is attenuated by appropriate optical attenuators (not shown). By way of example, an optical bent waveguide may be located at end 44 of bidirectional waveguide 19 to introduce optical bent loss for light termination.

[0050] Preferably, the number of optical ring resonators in second ring resonator arrangement 13 of dual band optical filter 34 is 2, which, given the double pass arrangement, provides good frequency selectivity at low system complexity and low optical loss. However, it will be appreciated that, in other embodiments, second ring resonator arrangement 13 includes 4, 6, 8 or a higher even number of optical ring resonators.

[0051] Referring to Figure 7, there is illustrated a fifth embodiment dual band optical filter 46. Filter 46 is very similar to filter 34 of Figure 5 but second ring resonator arrangement 13 in filter 46 includes an odd number of optical ring resonators arranged in

a linear coupled optical chain. As such, propagation of signal S_2 in waveguide 36 is in a direction to the left in Figure 7. Reflector 38 is coupled to the left hand side of waveguide 36 to reflect signal S_2 back along waveguide 36 and through a second pass of arrangement 13.

[0052] Referring to Figure 8, there is illustrated a sixth embodiment dual band optical filter 48. In filter 48, first ring resonator arrangement 11 operates in a similar manner to that described previously to output signal first frequency band f_2 . Second ring resonator arrangement 13 includes a side-coupled integrated spaced sequence of resonators (SCISSOR) resonator 50. The illustrated SCISSOR resonator includes two or more optical ring resonators arranged in a linear coupled optical chain extending between bidirectional waveguide 19 and bus waveguide 52. Bidirectional waveguide 19 is connected at a first end to 'Y' waveguide junction 7 and at a second end to an optical reflector 54 such as a reflective Bragg reflector, reflective etalon, loop mirror or other type of optically reflective device.

[0053] In operation, the SCISSOR resonator 50 operates to filter signal S_{thr} to produce a resonant passband equating to frequency band f_2 . By choosing ring resonators and bus waveguides having diameters and lengths that support the resonance condition for frequency band f_2 , those frequencies under resonance are coupled from bidirectional waveguide 19 to bus waveguide 52 through the ring resonators. If the signal propagating in bus waveguide 52 interferes constructively, it is coupled back in the input waveguide. Constructive interference is achieved if the round-trip phase between two or more rings is a multiple of 2π . This condition is satisfied when the centre-to-centre distance between adjacent ring resonators is a multiple of πR , where R is the radius of the rings. When this resonance condition is satisfied, the transmission spectrum at the output of the SCISSOR resonator 50 exhibits a very narrow frequency band corresponding to f_2 to define signal S_2 . Thus, the parameters that determine the peak frequency and shape of signal S_2 are the radii or diameters of the ring resonators and the spacing of the ring resonators.

[0054] After initial propagation through SCISSOR resonator 50, signal S_2 is reflected by reflector 54 and is returned through SCISSOR resonator 50 for a second time. This second pass acts to further shape the frequency band of signal S_2 around the peak frequency f_2 . The returned signal S_2 traverses bidirectional waveguide 19, couples to output waveguide 9 and is output together with signal S_1 as output signal S_{out} .

[0055] An alternate optical filter utilising a SCISSOR resonator is illustrated in Figure 9, which illustrates a seventh embodiment dual band optical filter 56. Filter 56 includes a

loop waveguide 58 coupled to bidirectional waveguide 19. In this embodiment, second ring resonator arrangement 13 includes a SCISSOR resonator 58 that operates in a similar manner to resonator 50 described above to output signal S_2 . The primary difference between filter 56 and filter 48 is that loop waveguide 58 is bidirectional and only a single pass of the SCISSOR resonator is utilised in filter 56.

[0056] Referring now to Figure 11, there is illustrated an eighth embodiment dual band optical filter 61. Filter 61 includes first ring resonator 11 disposed between input waveguide 5 and output waveguide 9 for filtering the first signal component S_1 from the input signal S_{in} in a similar manner to that described above in relation to filter 1. The first signal component S_1 , having first frequency band f_1 , is coupled to output waveguide 9 for output through the output port.

[0057] Input and output waveguides 5 and 9 are connected to define a continuous waveguide 63. The signal component not filtered by the first ring resonator 11 (S_{thr}) is coupled along continuous waveguide 63 and passed through a SCISSOR resonator 65. The SCISSOR resonator, which operates in a similar manner to that described above in relation to filter 56, filters the second signal component S_2 from S_{thr} and couples this signal component together with the first signal component S_1 to the output port. A key advantage of this 'feedback' type configuration is that it eliminates the usage of Y junctions, which incur a higher optical loss. The SCISSOR resonator 65 connects in parallel with the first ring resonator arrangement 11, thus simultaneously achieving signal filtering and circulation.

[0058] Referring now to Figure 12, there is illustrated a ninth embodiment dual band optical filter 67. Filter 67 includes first ring resonator 11 disposed between input waveguide 5 and output waveguide 9 for filtering the first signal component S_1 from the input signal S_{in} in a similar manner to that described above in relation to filter 1. The input waveguide 5 and output waveguide 9 are connected and together define a continuous curved waveguide 69. Curved waveguide 69 includes two 'U' shaped bends 71 and 73 across which two ring resonator arrangements 75 and 77 are disposed in a cascaded zigzag topology. Each ring resonator arrangement 75 and 77 has an even number of ring resonators positioned between the two parallel arms of the 'U' shaped bends of curved waveguide 69. By properly designing the parameters of the zigzags topology, a coherence effect similar to electromagnetically induced transparency (EIT) produces a filter passband with high Quality factor and ultra-narrow bandwidth. The frequency components selected by the EIT-like passband define the second signal component S_2 having second frequency

component f_2 , which is combined with signal component S_1 and transmitted to the output port.

[0059] Referring now to Figure 13, there is illustrated a tenth embodiment dual band optical filter 80. Filter 80 is similar to filter 67 of Figure 12 but comprises a SCISSOR resonator 82 disposed between input waveguide 5 and output waveguide 9 instead of the first ring resonator arrangement 11.

[0060] In each of the embodiments described above, the dual band optical filter includes a first optical ring resonator device (end coupled ring resonator arrangement or SCISSOR resonator arrangement) for filtering first signal component S_1 , having first frequency band f_1 and a second optical ring resonator device (end coupled ring resonator arrangement or SCISSOR resonator) for filtering second signal component S_2 , having first frequency band f_2 .

[0061] The dual band optical filters described above provide for the construction of an optical receiver, which is a second aspect of the present invention. Referring to Figure 14 there is illustrated schematically an exemplary optical receiver 84 including a bank 86 of dual band optical filters 88-90. In the illustrated embodiment, each filter in bank 86 includes a first optical ring resonator arrangement 92 having three ring resonators and a second optical ring resonator arrangement 94 having two optical ring resonators. However, any of the filters described above are suitable for use in receiver 84. Depending on the particular application of receiver 84, some filter embodiments may be more preferable than others.

[0062] Receiver 84 includes an optical source 96 such as a narrowband laser to provide an optical carrier signal 98 at a carrier frequency f_c . The carrier signal 98 is input to an electro-optic modulator 100 through an optical input 102 to modulate the optical carrier signal with an electromagnetic (EM) signal 104 to be analysed. The EM signal 104 is typically a microwave frequency signal but, more generally, may be any signal within the radio frequency signal band. EM signal 104 is received from an antenna 106 and having a peak frequency (or frequencies) f_{RF} . EM signal 104 is input to modulator 100 through a corresponding EM input 108. Modulator 100 generates a modulated optical signal 110, which includes power at the carrier frequency and one or more sidebands depending on the modulation technique implemented by modulator 100 and the peak frequencies contained in signal 104.

[0063] Modulated optical signal 110 is passed through an optical isolator 112 to restrict backward propagation of signals to modulator 100. Signal 112 is then passed through a

power splitter 114 to split the power equally along respective feed waveguides to corresponding filters of bank 86. Each filter includes the above described first and second ring resonator arrangements to output respective dual band filtered optical signals (S_1 to S_N), each having respective first and second frequency bands ($f_{1,1}$ to $f_{1,N}$ and $f_{2,1}$ to $f_{2,N}$). The different frequency bands are achieved by each filter using optical ring resonators of differing diameter. The number N of filters in bank 86 is dependent upon the application of receiver. In applications requiring detection of a large number of channels, a greater number of filters is required.

[0064] The respective filtered optical signals are coupled to one or more photodetectors (not shown) or other type of optical detector configured to detect the dual band filtered optical signals to achieve frequency channelization of the unknown EM signal 104. In one embodiment, each filter is coupled to a respective photodetector for detecting each individual signal. In another embodiment, each filter in bank 86 is connected as separate inputs to a common spectral analyser which scans across a spectral range encompassing signals S_1 to S_N .

[0065] In various receiver applications, it is preferable for the optical ring resonator arrangements to be designed such that each of the respective first frequency bands are centred around the known carrier frequency f_c of the optical carrier signal 98. Further, the respective second frequency bands of separate filters are staggered in frequency across a predefined frequency range so as to detect likely frequencies equal to an upper modulated sideband $f_c + f_{RF}$ of the unknown EM signal 104. Upon detection of the upper modulated sideband $f_c + f_{RF}$, the EM signal 104 can be extracted by subtracting the detected carrier frequency f_c to obtain f_{RF} (down conversion) or via an AC-coupled photodetector to remove the low frequency components at f_c while the high frequency component at f_{RF} remains.

SIMULATION RESULTS

[0066] The optical receiver 84 illustrated in Figure 14 was simulated to verify its performance using the MATLAB™ and computer simulation software developed by MathWorks, Inc. and the VPITransmissionMaker™ computer simulation software developed by VPIphotonics Inc. Various exemplary results of the simulations are illustrated in Figures 15 to 18.

[0067] In Figure 15, the simulated channel responses of eight dual band optical filters (as generated in the MATLAB™ software) are displayed. From the graph, it can be seen that the channel responses show two distinct passbands in the spectrum. The narrow

passband on the left is common to each filter signal and represents the carrier signal, f_c . The wider passbands extending from 3 GHz to 10 GHz and spaced at 1 GHz intervals represent the second frequency bands $f_{2,1}$ to $f_{2,8}$ selected to capture the upper modulated sidebands $f_c + f_{RF}$.

[0068] In Figures 16 to 18, three RF frequency signals of $f_{RF} = 10$ GHz, 20 GHz and 30 GHz were modulated onto the optical carrier using the VPITransmissionMaker™ software. With 1 GHz channel spacing, the RF signals were detected in the 10th, 20th, and 30th channels (filters) of the channelized dual band optical filter output. As observed in the graph, each RF tone along with the carrier is correctly channelized while the other frequencies are significantly suppressed. Thus, to fully detect these RF signals, the receiver would require at least 30 filters having second frequency band f_2 spaced at 1 GHz.

[0069] The present invention overcomes the fundamental limitations of the prior art by introducing a filter bank consisting of a number of dual band optical filters in a novel reflective structure. The significance of having two passbands allows selected transmission of both the carrier and modulated signals simultaneously, thus eradicating the need for additional couplers. As such, intermediate frequencies with small RF power variations can be obtained by optical down conversion or AC coupled photodetector on chip. In addition, due to the introduction of the reflective or loop structures, the filtering performance is largely improved as compared to devices without a reflector or loop. The single port nature of existing reflective structures requires optical circulators to distinguish between the input and output signals. However, the reflective or loop structure of the present invention eliminates the use of circulators to isolate the input and reflected output, which further increases its ease of photonic integration. In particular, the use of the reflective structure allows the entire receiver to be integrated onto a photonic chip, which is difficult to achieve using optical circulators.

[0070] By way of example, the present invention has useful applications in optical single sideband modulation, optical electrical oscillators and down converters/photonic mixers.

DEFINITIONS

[0071] Throughout this specification, use of the terms “photonic” and “optical” in the sense of “optical signals” or the like are used to refer to the electromagnetic spectrum/radiation in one or more of the visible, ultraviolet or infrared frequency ranges. The optical signals include a finite definable frequency spectrum in the spectral domain,

neglecting noise signals, which may occur at any frequency. Use of the term 'band', 'frequency band' or the like is intended to mean a finite frequency range having optical power above a designated threshold or detectible power level. Frequency bands are typically identified by their central frequency or frequency of maximum power. Thus, a frequency band having a frequency ' f_1 ' includes a finite frequency range about a peak frequency f_1 .

[0072] Use of the term "microwave" in the sense of a "microwave signal" is used to refer to an electromagnetic signal in the microwave range of frequencies, which extends between about 300 MHz to 300 GHz.

[0073] Use of the term "radio frequency" in the sense of a "radio frequency signal" is used to refer to an electromagnetic signal in the range of frequencies extending between about 3 KHz to 300 GHz and encompasses the microwave range of frequencies.

[0074] Throughout this specification, use of the term "element" or "optical element" is intended to mean either a single unitary component or a collection of components that combine to perform a specific function or purpose.

[0075] Reference throughout this specification to "one embodiment", "some embodiments" or "an embodiment" means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the present disclosure. Thus, appearances of the phrases "in one embodiment", "in some embodiments" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner, as would be apparent to one of ordinary skill in the art from this disclosure, in one or more embodiments.

[0076] As used herein, unless otherwise specified the use of the ordinal adjectives "first", "second", "third", etc., to describe a common object, merely indicate that different instances of like objects are being referred to, and are not intended to imply that the objects so described must be in a given sequence, either temporally, spatially, in ranking, or in any other manner.

[0077] In the claims below and the description herein, any one of the terms comprising, comprised of or which comprises is an open term that means including at least the elements/features that follow, but not excluding others. Thus, the term comprising, when used in the claims, should not be interpreted as being limitative to the means or elements or steps listed thereafter. For example, the scope of the expression a device comprising A

and B should not be limited to devices consisting only of elements A and B. Any one of the terms including or which includes or that includes as used herein is also an open term that also means including at least the elements/features that follow the term, but not excluding others. Thus, including is synonymous with and means comprising.

[0078] It should be appreciated that in the above description of exemplary embodiments of the disclosure, various features of the disclosure are sometimes grouped together in a single embodiment, Fig., or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of one or more of the various inventive aspects. This method of disclosure, however, is not to be interpreted as reflecting an intention that the claims require more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the claims following the Detailed Description are hereby expressly incorporated into this Detailed Description, with each claim standing on its own as a separate embodiment of this disclosure.

[0079] Furthermore, while some embodiments described herein include some but not other features included in other embodiments, combinations of features of different embodiments are meant to be within the scope of the disclosure, and form different embodiments, as would be understood by those skilled in the art. For example, in the following claims, any of the claimed embodiments can be used in any combination.

[0080] In the description provided herein, numerous specific details are set forth. However, it is understood that embodiments of the disclosure may be practiced without these specific details. In other instances, well-known methods, structures and techniques have not been shown in detail in order not to obscure an understanding of this description.

[0081] Similarly, it is to be noticed that the term coupled, when used in the claims, should not be interpreted as being limited to direct connections only. The terms “coupled” and “connected,” along with their derivatives, may be used. It should be understood that these terms are not intended as synonyms for each other. Thus, the scope of the expression a device A coupled to a device B should not be limited to devices or systems wherein an output of device A is directly connected to an input of device B. It means that there exists a path between an output of A and an input of B which may be a path including other devices or means. “Coupled” may mean that two or more elements are either in direct physical, electrical or optical contact, or that two or more elements are not in direct contact with each other but yet still co-operate or interact with each other.

[0082] Thus, while there has been described what are believed to be the preferred embodiments of the disclosure, those skilled in the art will recognize that other and further modifications may be made thereto without departing from the spirit of the disclosure, and it is intended to claim all such changes and modifications as fall within the scope of the disclosure. For example, any formulas given above are merely representative of procedures that may be used. Functionality may be added or deleted from the block diagrams and operations may be interchanged among functional blocks. Steps may be added or deleted to methods described within the scope of the present disclosure.

We claim:

1. A dual band optical filter including:
 - an input waveguide to input an optical signal;
 - an output waveguide to output a filtered optical signal;
 - a first filter path disposed between the input waveguide and the output waveguide and configured to couple a first frequency component of the optical signal to the output waveguide as a first band of the filtered optical signal; and
 - a second filter path disposed between the input waveguide and the output waveguide and configured to couple a second frequency component of the optical signal to the output waveguide to form a second band of the filtered optical signal.
2. A dual band optical filter according to claim 1 wherein the first filter path includes a first ring resonator arrangement coupled at a first end to the input waveguide and at a second end to the output waveguide, the first ring resonator arrangement including at least one optical ring resonator configured to couple the first frequency component of the optical signal from the input waveguide to the output waveguide.
3. A dual band optical filter according to claim 2 wherein the second filter path includes a second ring resonator arrangement, the second ring resonator arrangement including at least one optical ring resonator configured to couple the second frequency component of the optical signal from the input waveguide to the output waveguide.
4. A dual band optical filter according to claim 3 wherein the input waveguide and the output waveguide are connected to define first and second arms of a first 'Y' shaped waveguide junction, a third arm of the first 'Y' shaped waveguide junction defining a bidirectional waveguide that is coupled to the second ring resonator arrangement.
5. A dual band optical filter according to claim 4 wherein the bidirectional waveguide defines a first arm of a second 'Y' shaped waveguide junction, a second arm of the second 'Y' shaped waveguide junction being coupled to a first end of the second ring resonator arrangement and a third arm of the second 'Y' shaped waveguide junction being coupled to a second end of the second ring resonator arrangement, the bidirectional waveguide being configured to couple the optical signal from the first 'Y' shaped waveguide junction to the second 'Y' shaped waveguide junction and

to couple the second frequency component from the second ring resonator arrangement to the first 'Y' shaped waveguide junction.

6. A dual band optical filter according to claim 4 wherein the bidirectional waveguide is coupled directly to the second ring resonator arrangement.
7. A dual band optical filter according to claim 6 wherein a first end of the second ring resonator arrangement is coupled to the bidirectional waveguide and a second end of the second ring resonator arrangement is coupled to a reflective waveguide structure configured to reflect the second frequency component through a second pass of the second ring resonator arrangement and back to the bidirectional waveguide.
8. A dual band optical filter according to claim 6 or claim 7 wherein the waveguide reflector is a Bragg grating.
9. A dual band optical filter according to claim 6 or claim 7 wherein the waveguide reflector is a loop mirror.
10. A dual band optical filter according to claim 3 or claim 6 wherein the second ring resonator arrangement includes a plurality of optical ring resonators disposed in a coupled array extending parallel to a coupling waveguide in a side-coupled integrated spaced sequence of resonators (SCISSOR) arrangement.
11. A dual band optical filter according to claim 4 wherein the bidirectional waveguide is coupled to a loop waveguide and wherein the second ring resonator arrangement is disposed along the loop and includes a plurality of optical ring resonators disposed along a portion of the loop waveguide in a coupled array and extending parallel to a coupling waveguide in a side-coupled integrated spaced sequence of resonators (SCISSOR) arrangement.
12. A dual band optical filter according to any one of claims 2 to 11 wherein the first ring resonator arrangement includes a plurality of coupled optical ring resonators.
13. A dual band optical filter according to any one of claims 2 to 12 wherein the first ring resonator arrangement includes an odd number of coupled optical ring resonators disposed in an optical chain.

14. A dual band optical filter according to claim 13 wherein the first ring resonator arrangement includes three coupled optical ring resonators disposed in an optical chain.
15. A dual band optical filter according to any one of the preceding claims wherein the second ring resonator arrangement includes a plurality of coupled optical ring resonators disposed in an optical chain.
16. A dual band optical filter according to claim 15 wherein the second ring resonator arrangement includes an even number of optical ring resonators disposed in an optical chain.
17. A dual band optical filter according to claim 16 wherein the second ring resonator arrangement includes two coupled optical ring resonators.
18. A dual band optical filter according to claim 2 wherein the second filter path includes second and third ring resonator arrangements, the second and third ring resonator arrangements being disposed at respective bends along the second filter path and each including an even number of optical ring resonators configured to couple the second frequency component of the optical signal from the input waveguide to the output waveguide.
19. A dual band optical filter according to claim 2 or claim 18 wherein the first ring resonator arrangement includes a plurality of optical ring resonators disposed in a coupled array extending parallel to a coupling waveguide in a side-coupled integrated spaced sequence of resonators (SCISSOR) arrangement.
20. A dual band optical filter according to any one of the preceding claims formed on a photonic chip.
21. A photonic receiver including:
 - an optical source to provide an optical carrier signal;
 - an input for receiving an electromagnetic signal to be analysed;
 - an electro-optic modulator to modulate the optical carrier signal with the electromagnetic signal so as to generate a modulated optical signal;

one or more dual band optical filters according to any one of the preceding claims, each configured to receive the modulated signal and output a dual band filtered modulated signal; and

one or more photodetectors configured to detect the dual band filtered modulated signal.

22. A photonic receiver according to claim 21 wherein the first band is centred around a carrier frequency (f_c) of the optical carrier signal.
23. A photonic receiver according to claim 22 wherein the second band is centred around a frequency equal to $f_c + f_i$, where f_i is a frequency of the input signal to be analysed.
24. A photonic receiver according to any one of claims 21 to 23 including a power splitter disposed intermediate the optical modulator and the one or more dual band optical filters, the power splitter configured to split the optical power of the modulated signal equally between each of the one or more dual band optical filters.
25. A photonic receiver according to any one of claims 21 to 23 formed on a photonic chip.
26. A photonic receiver including:
 - a narrowband optical light source for emitting a first optical signal;
 - a first optical modulator modulating the first optical signal in accordance with an externally received electromagnetic signal so as to produce a modulated optical signal;
 - a series of optical resonator structures coupled to the modulated optical signal and outputting at least an optical sideband signal from the modulated optical signal.
27. A photonic receiver according to claim 26 wherein each of the optical resonator structures include:
 - a first coupled resonator optical waveguide interconnected to a second coupled resonator optical waveguide to separate the sideband signal and modulated optical signal.
28. A photonic receiver according to claim 26 or claim 27 wherein the optical ring resonator structures output a series of pass band signals.

29. A photonic receiver according to claim 28 wherein the first coupled resonator optical waveguides include optical ring resonators.
30. A photonic receiver according to any one of claims 26 to 29 wherein a plurality of sideband signals are output from the optical resonator structures.

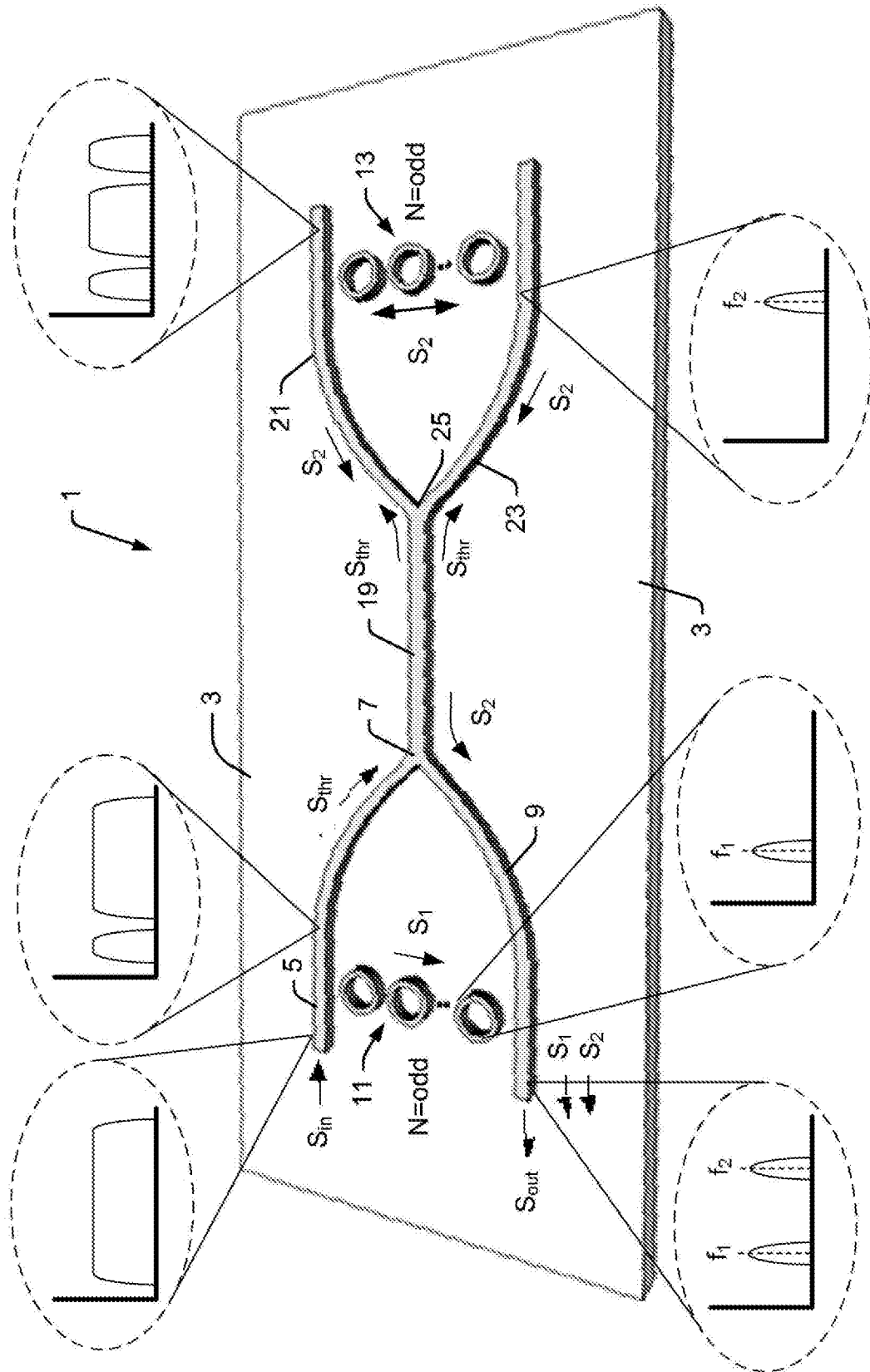


Figure 1

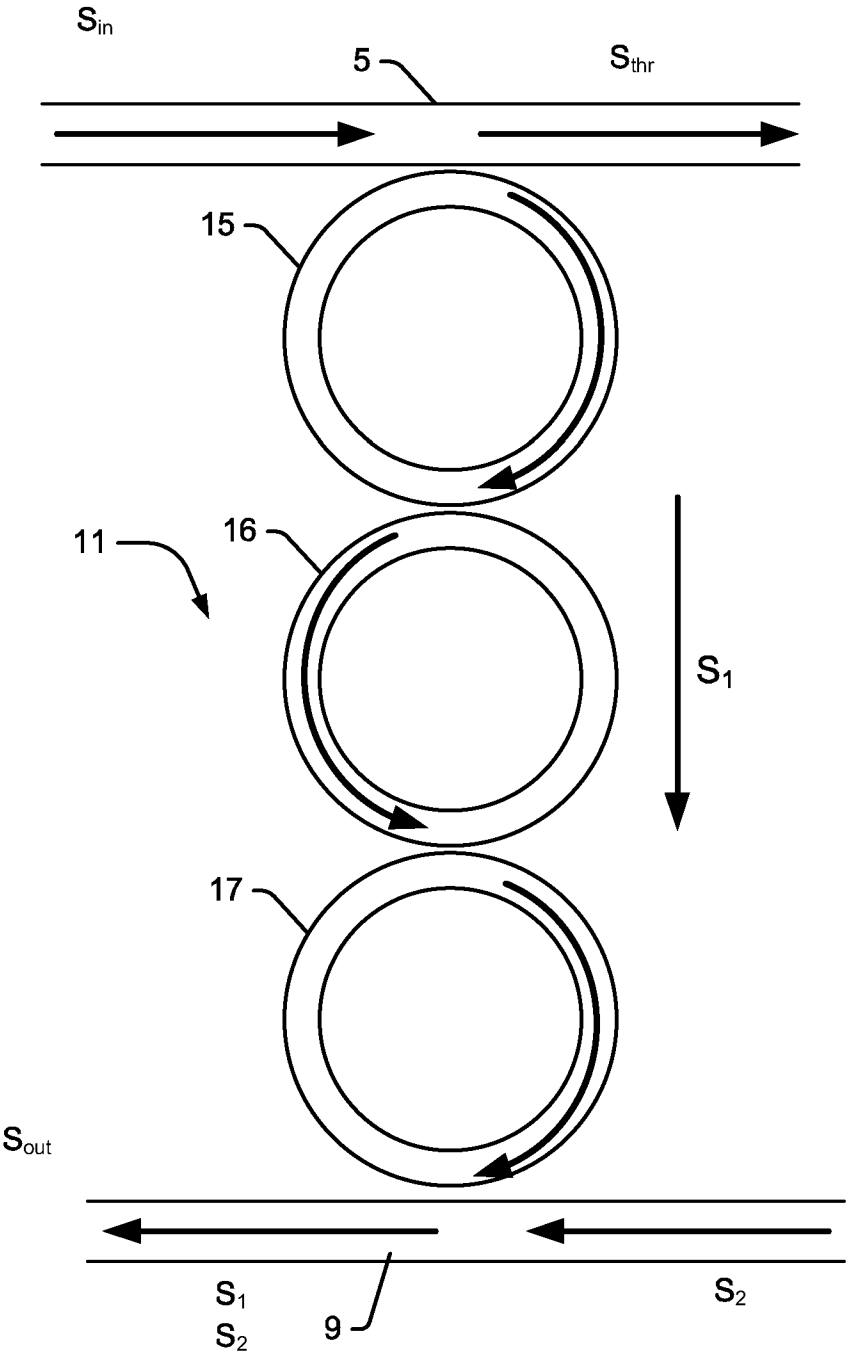


Figure 2

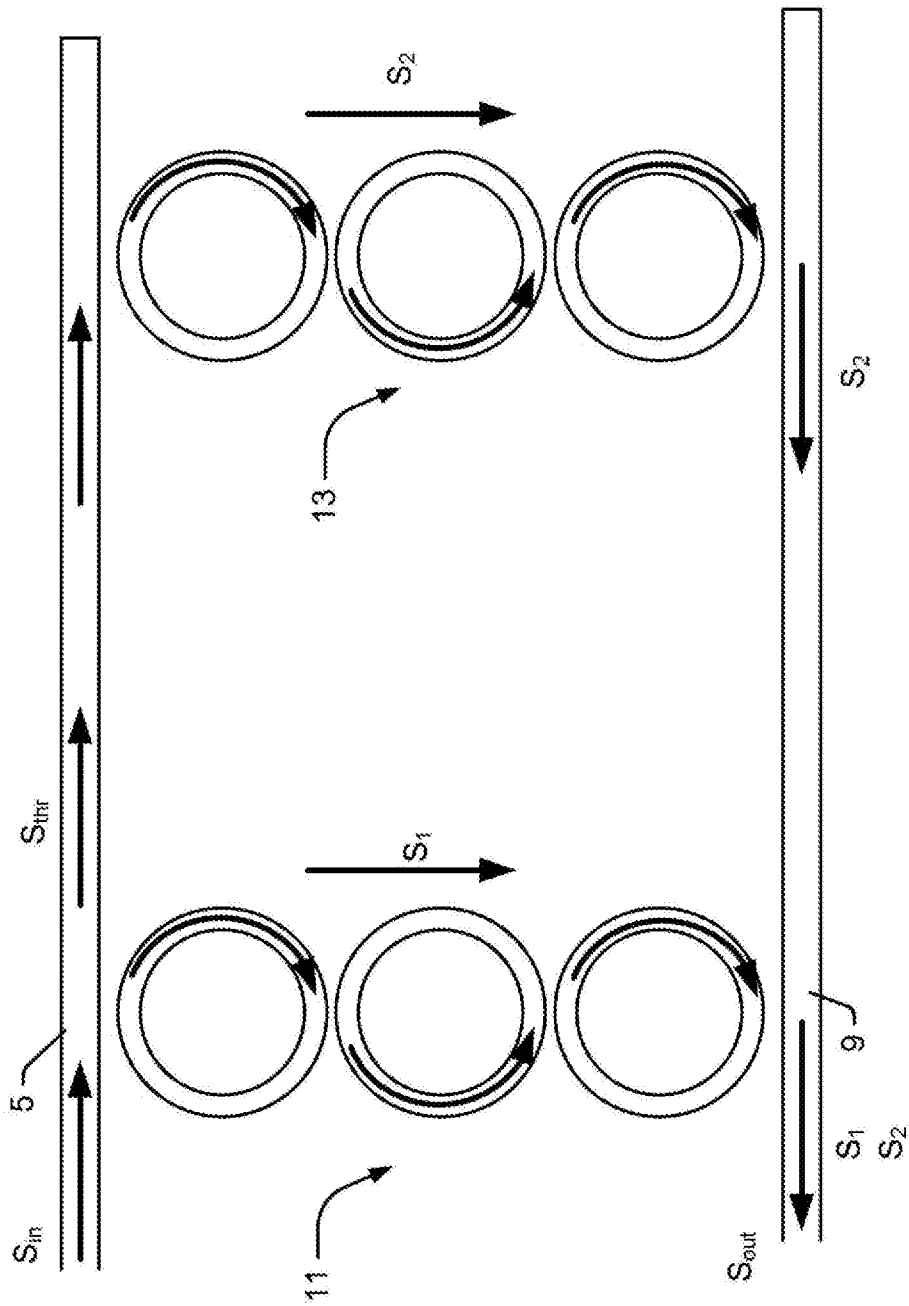


Figure 3

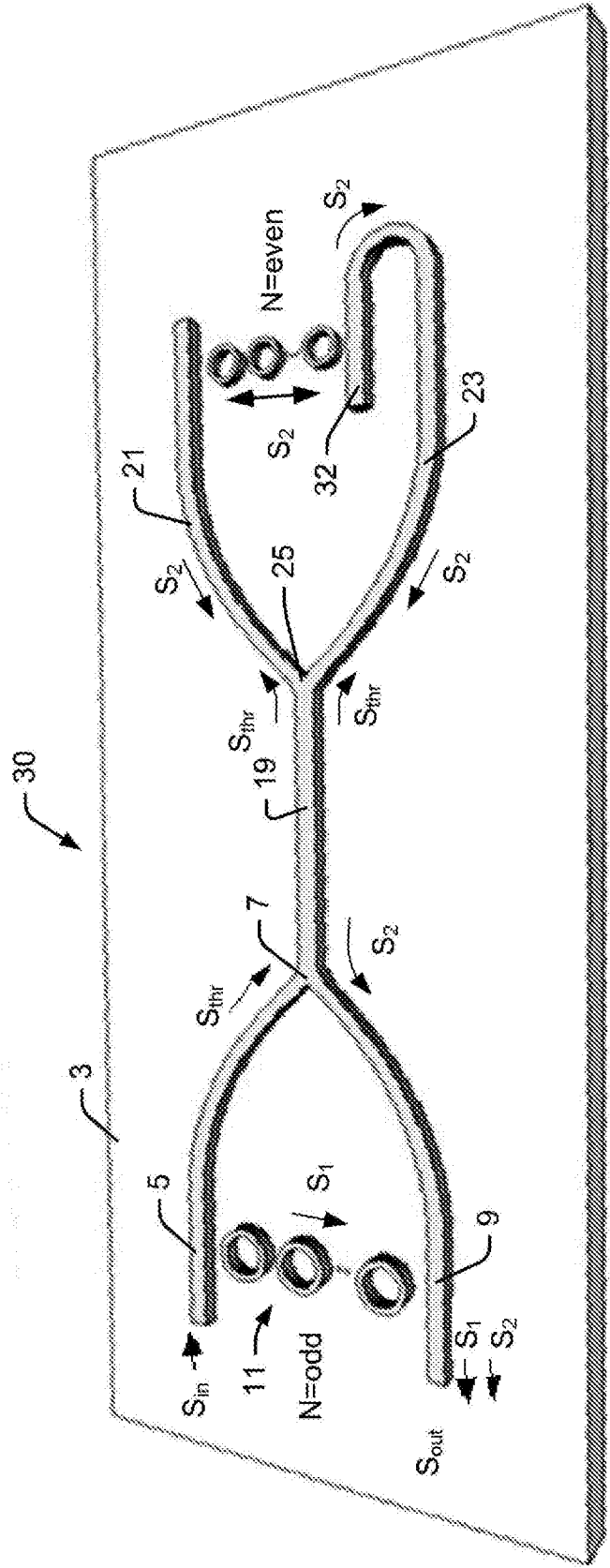


Figure 4

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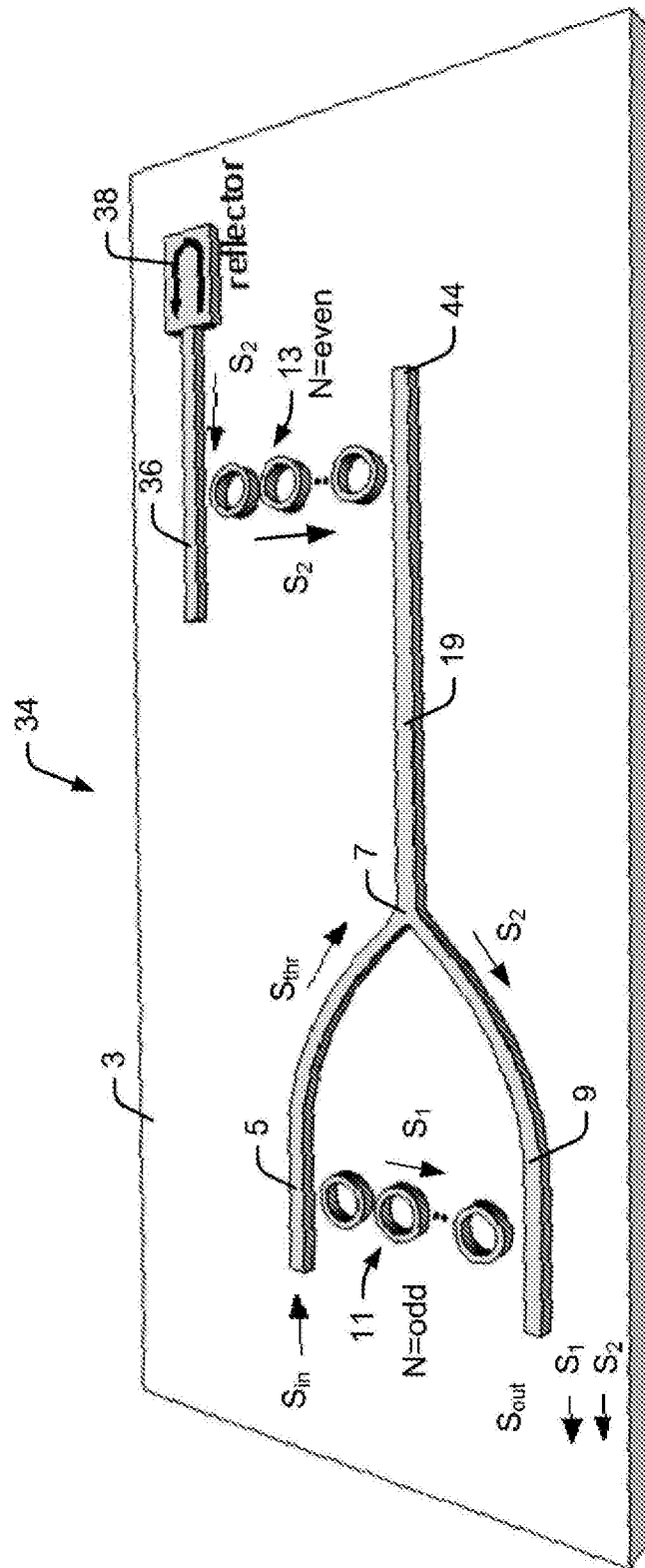


Figure 5

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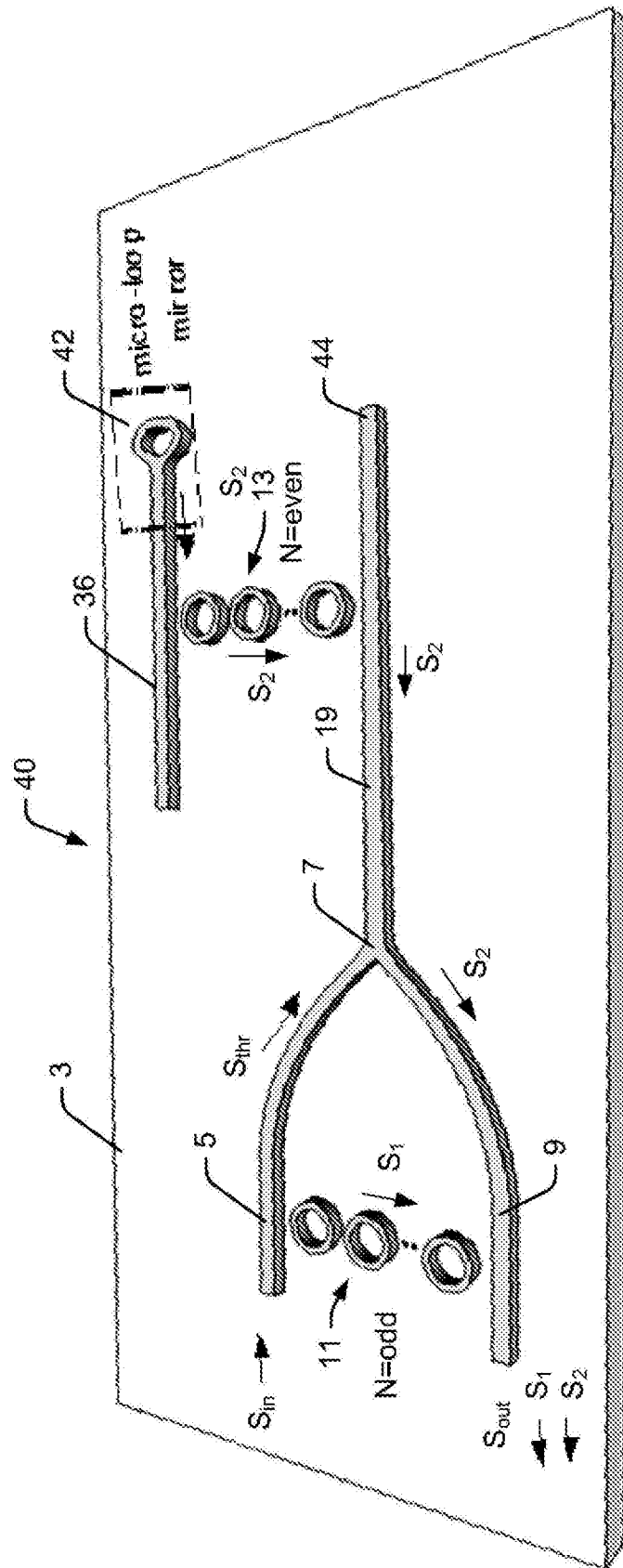


Figure 6

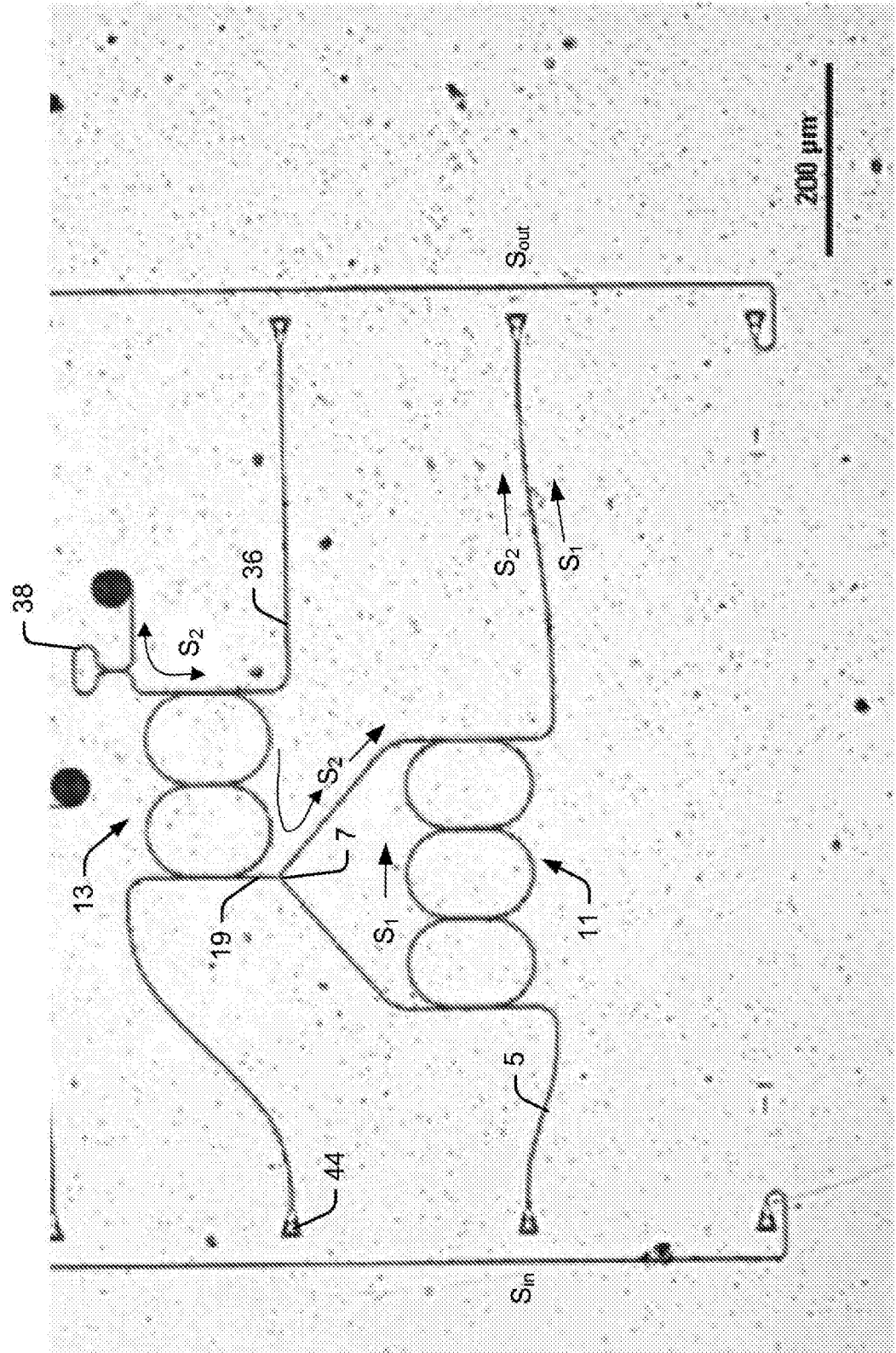


Figure 7

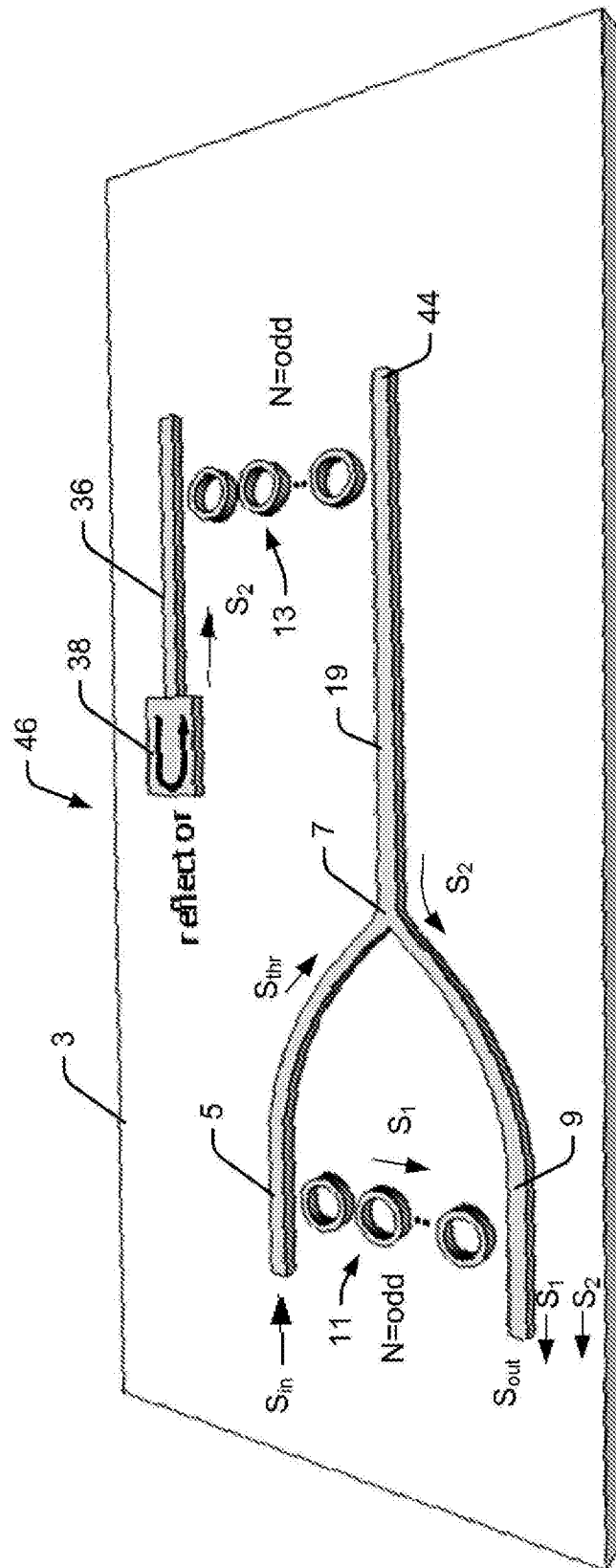


Figure 8

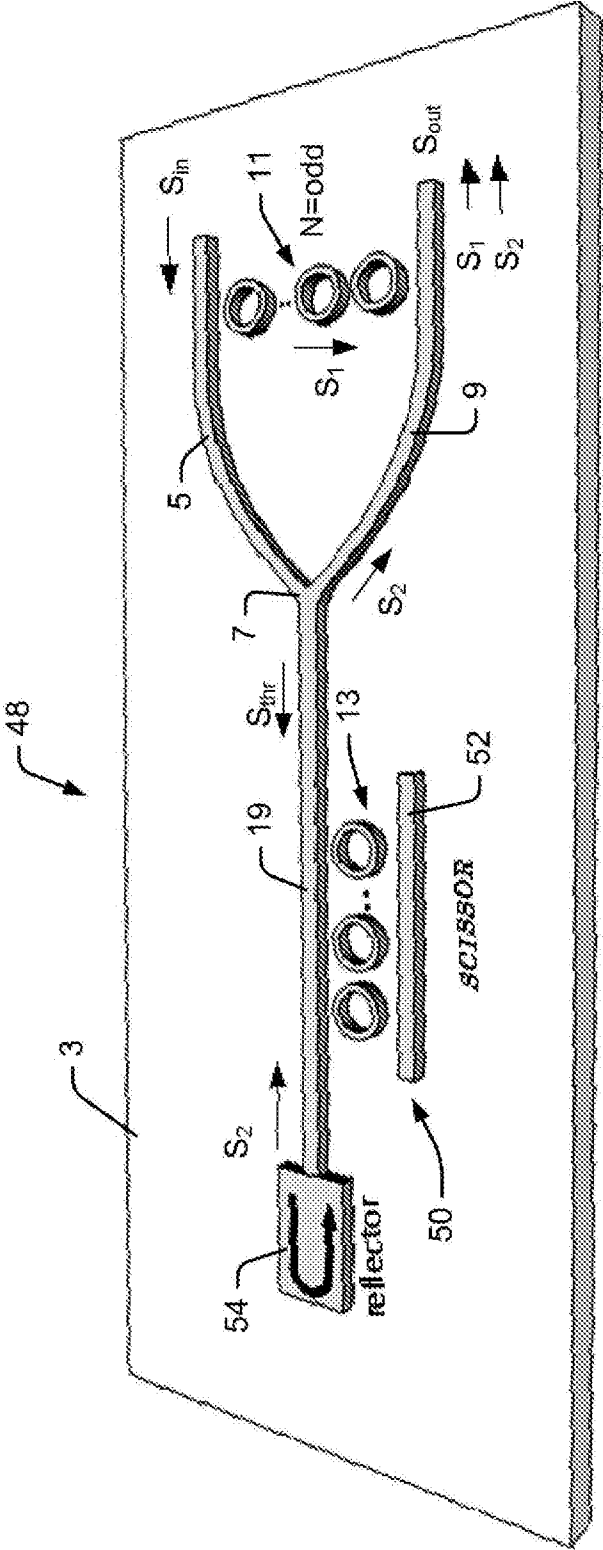


Figure 9

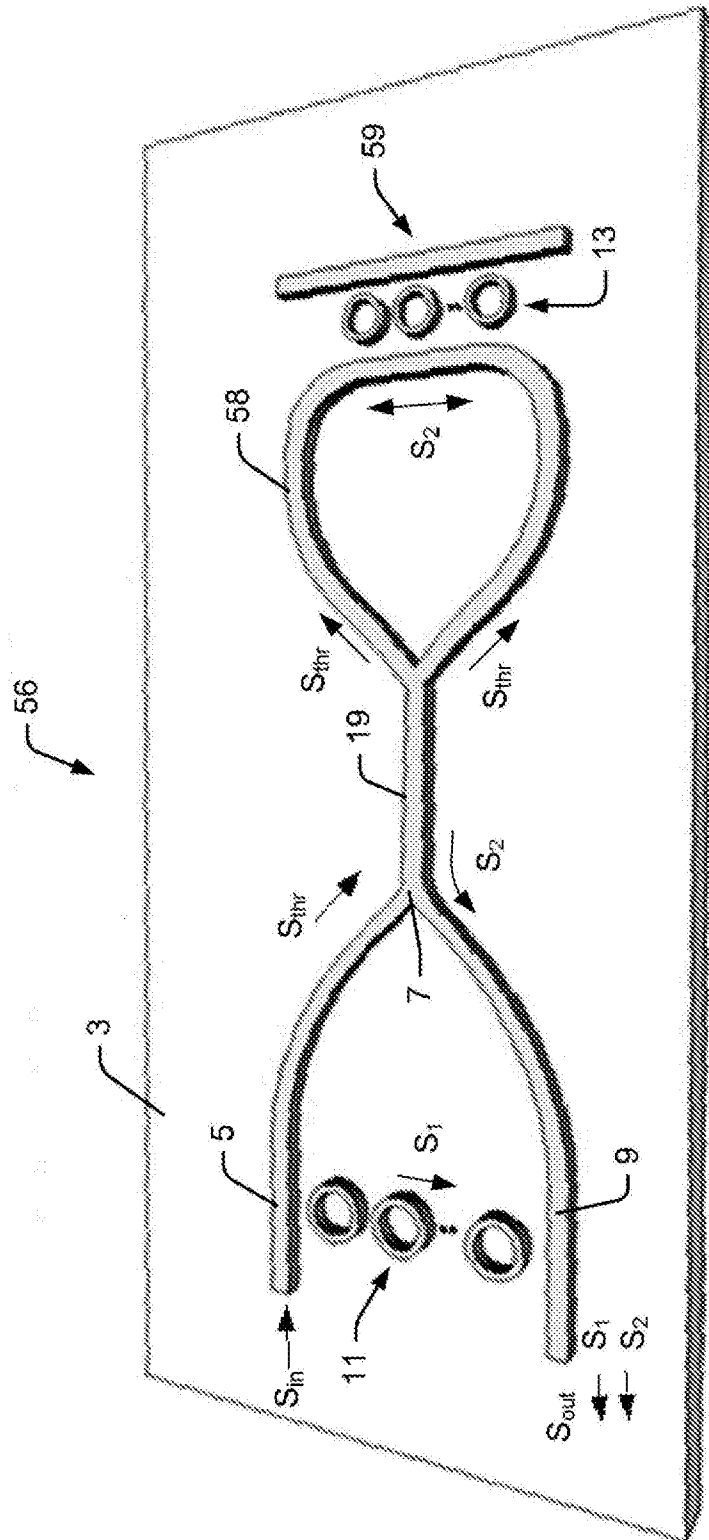


Figure 10

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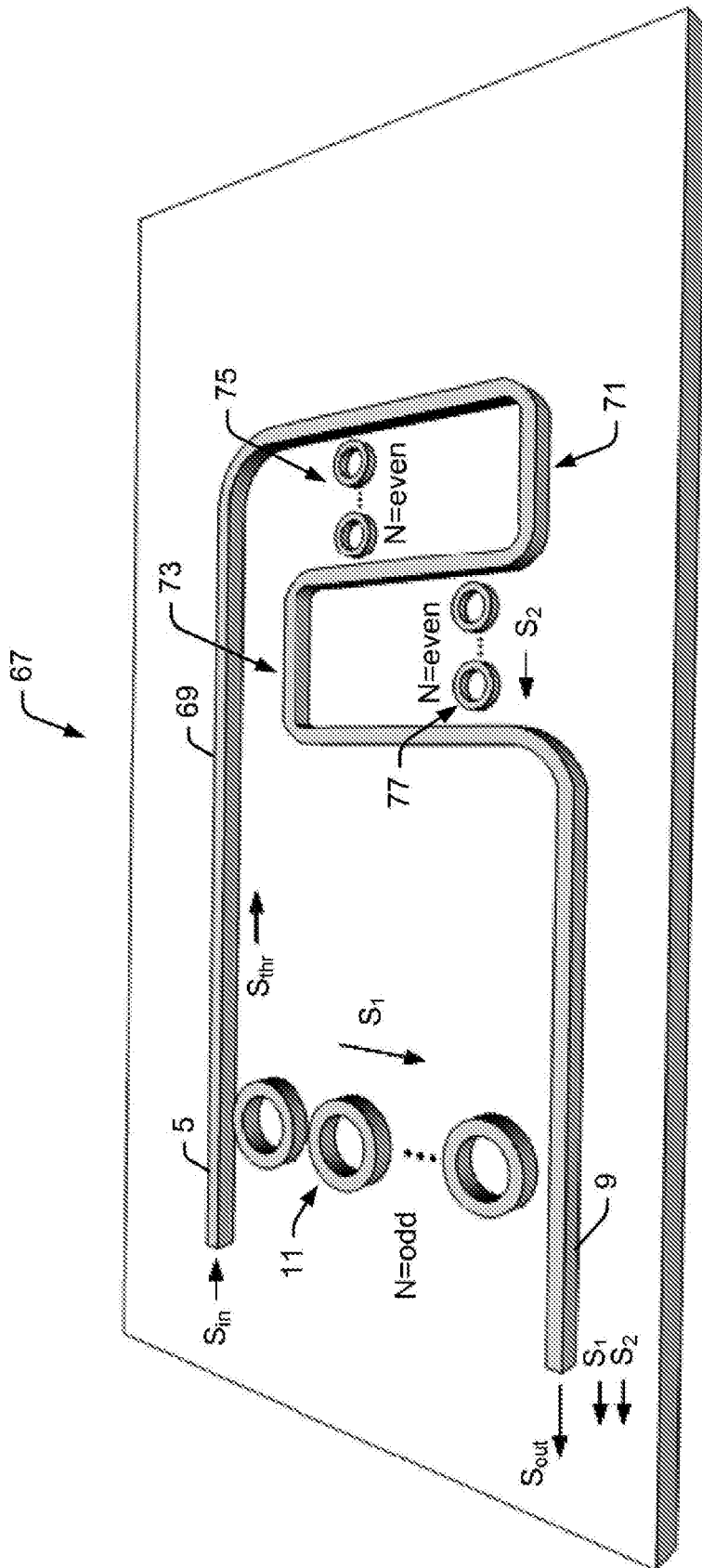


Figure 12

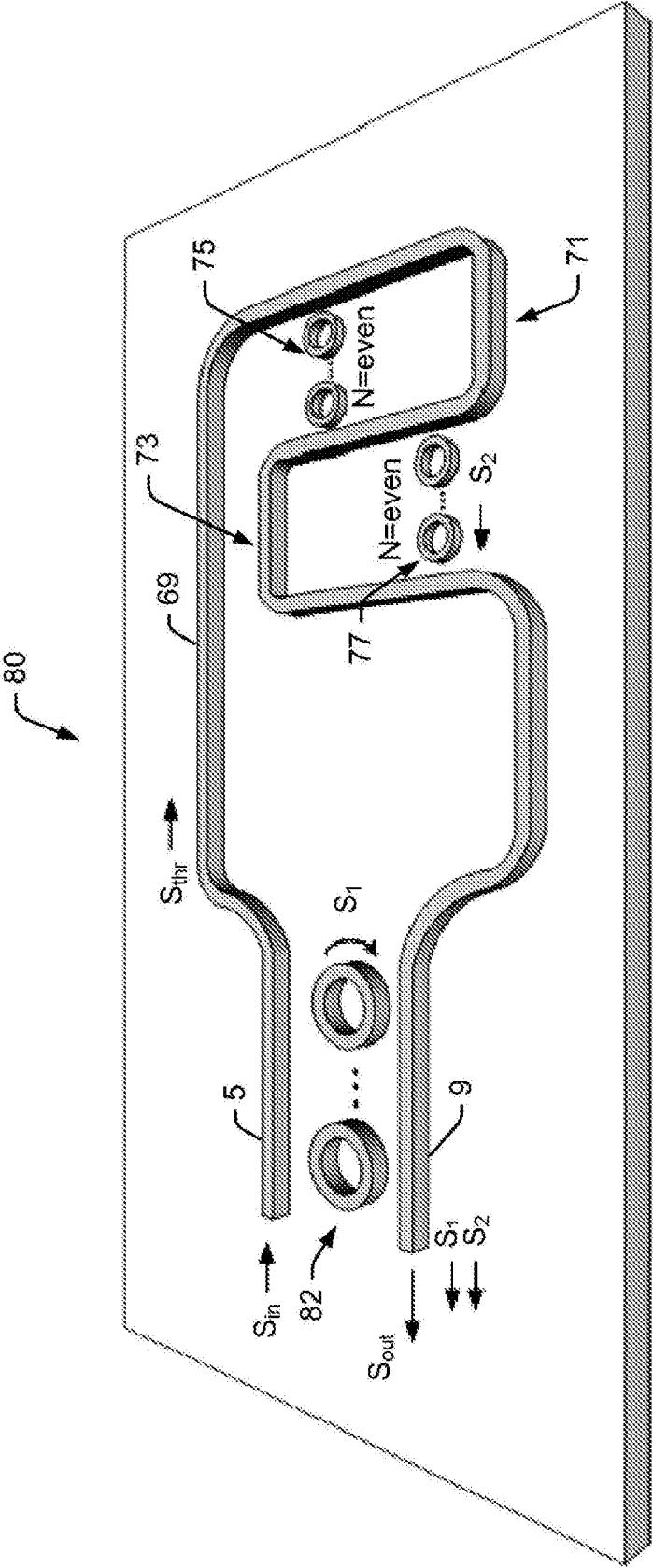


Figure 13

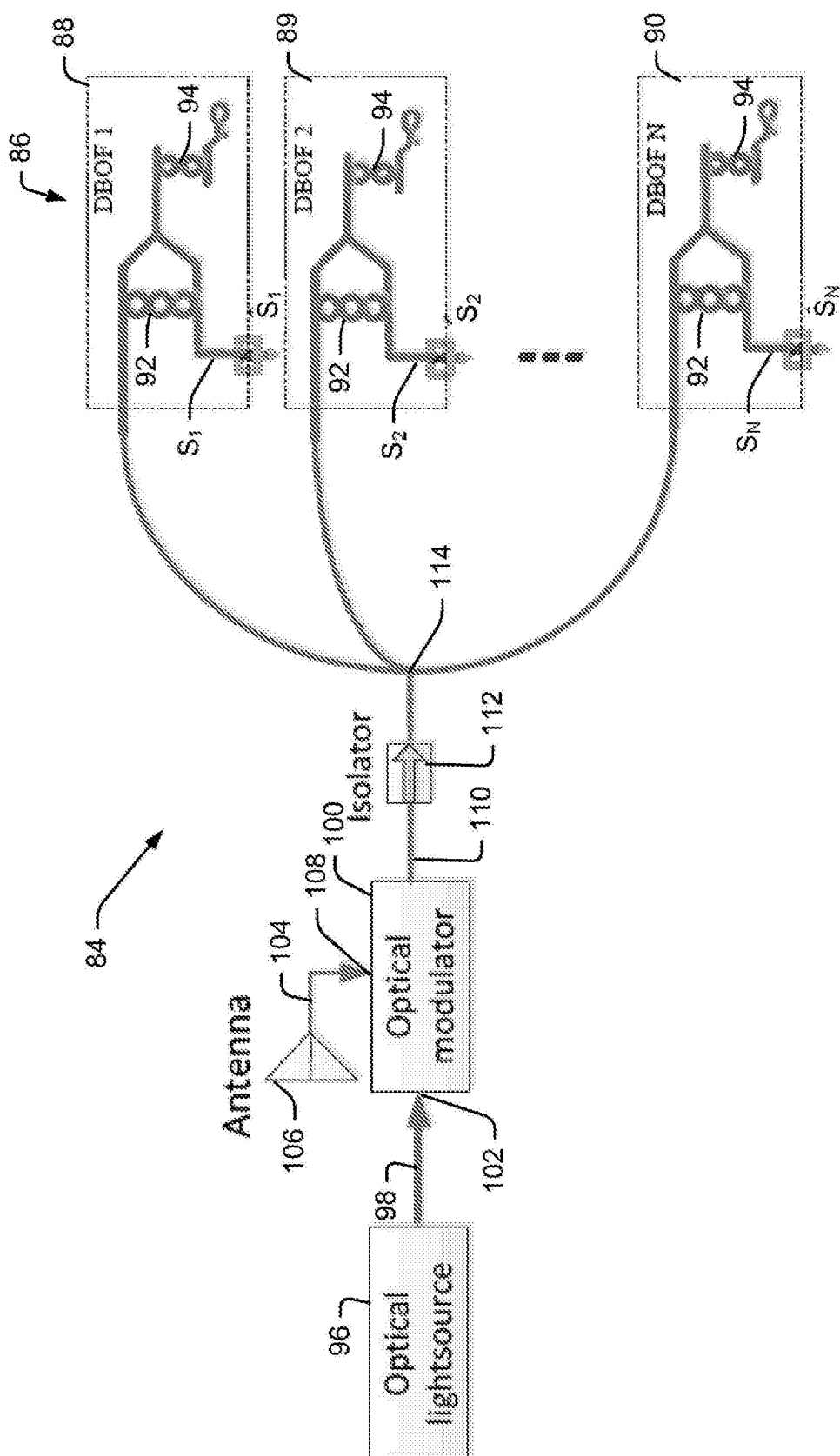


Figure 14

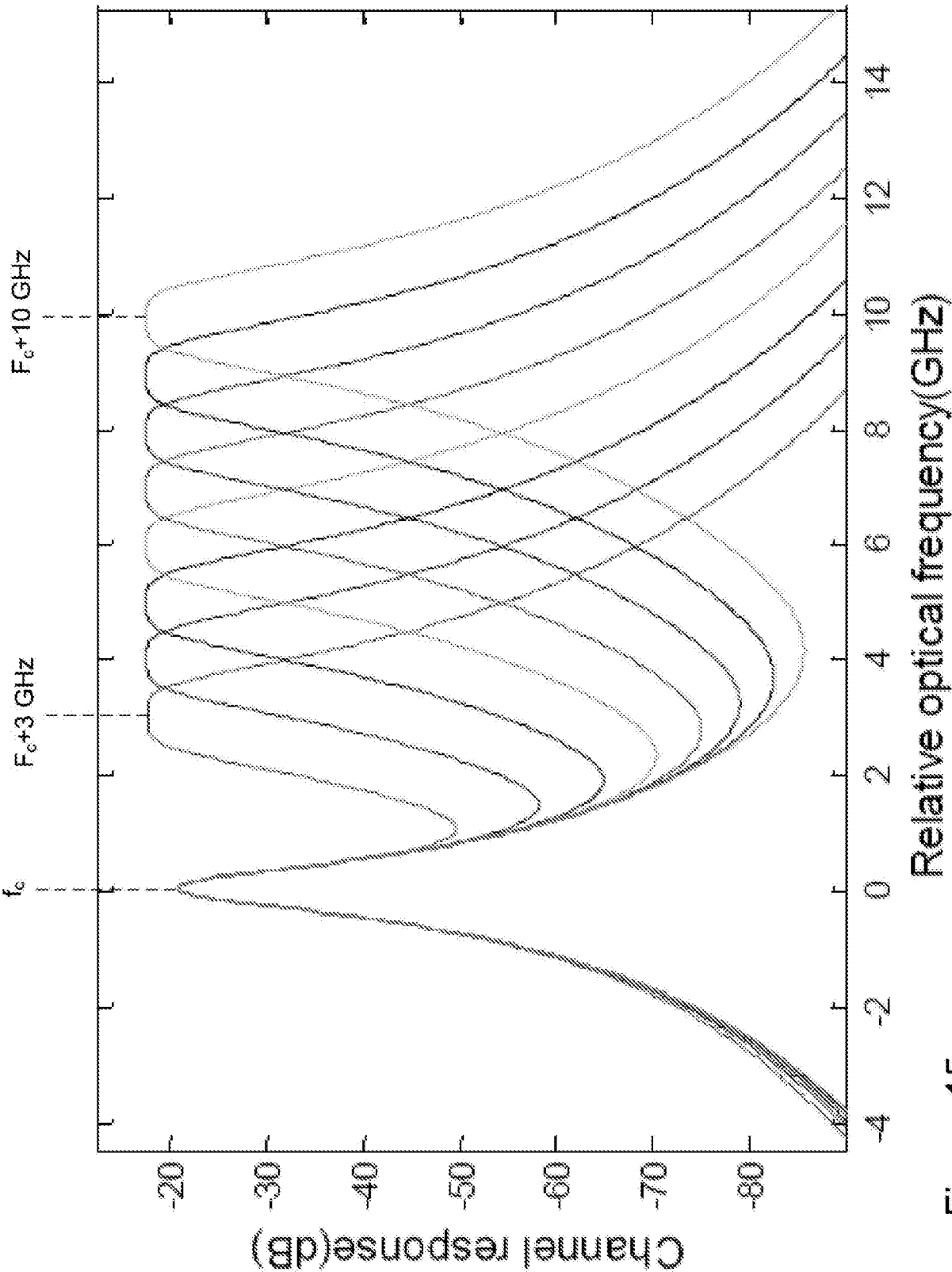


Figure 15

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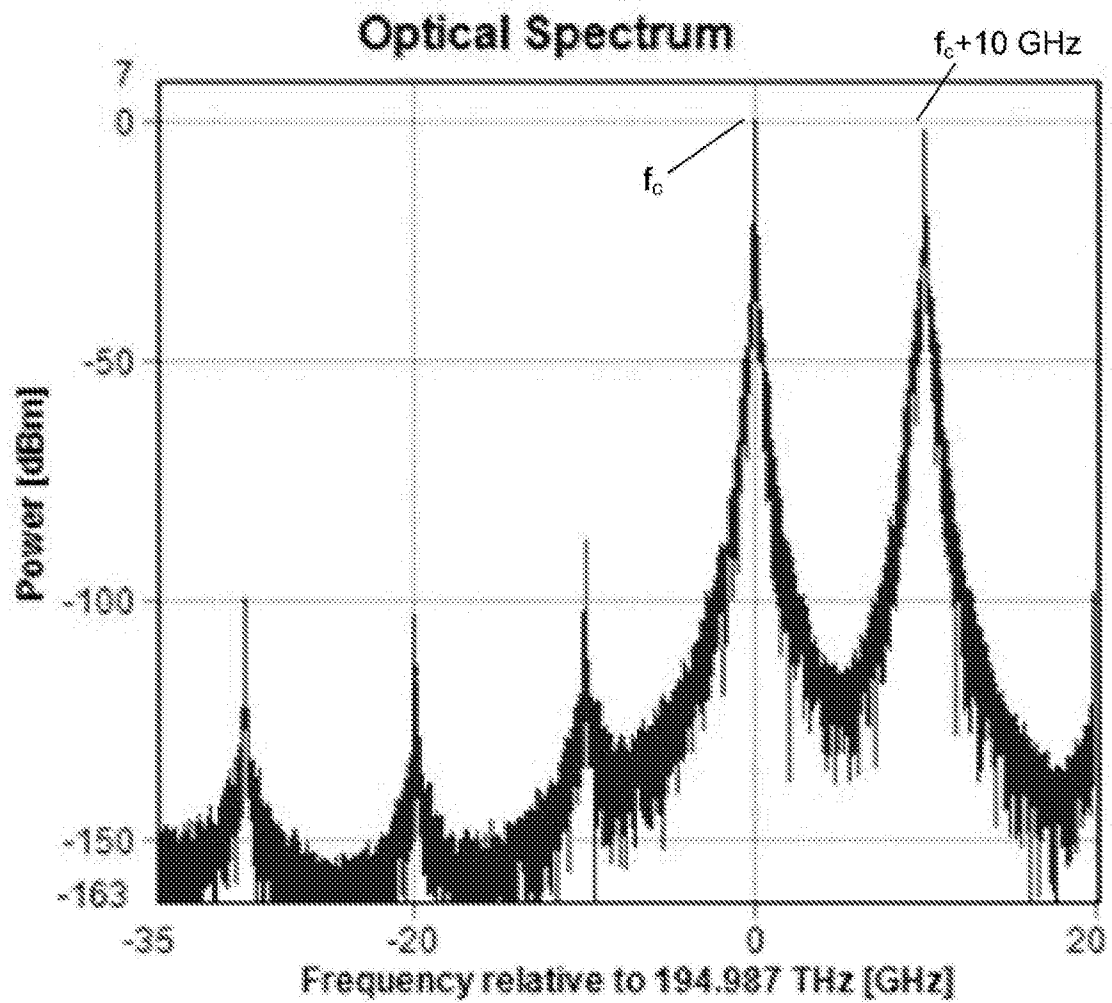


Figure 16

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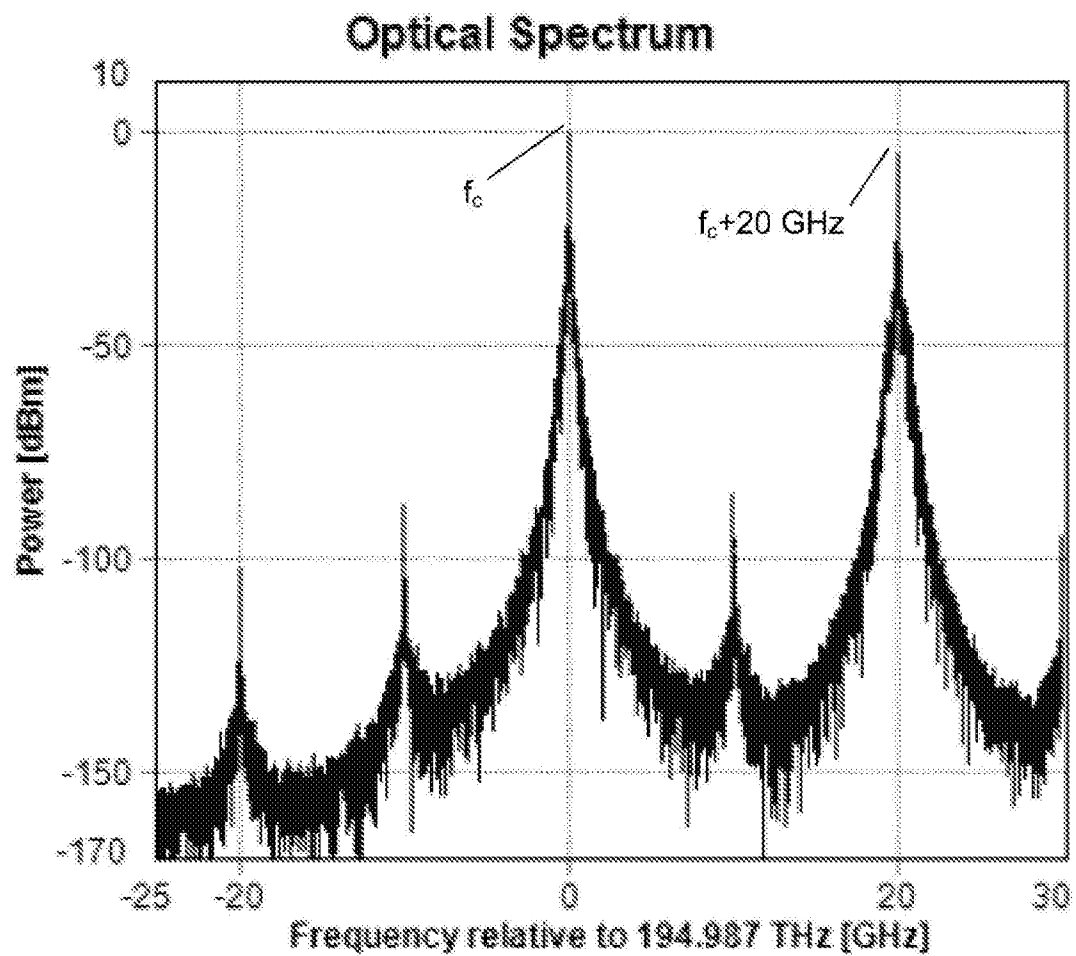


Figure 17

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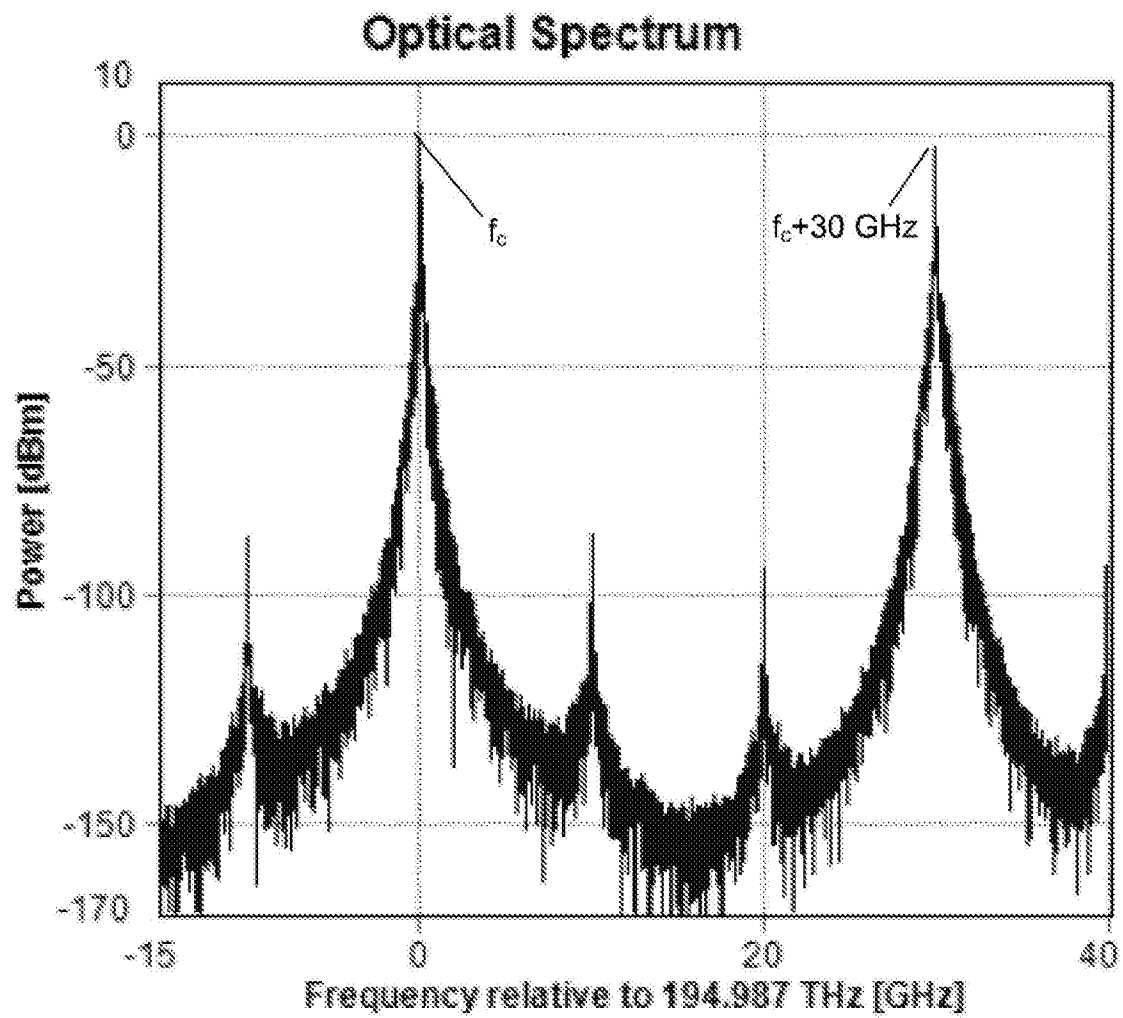


Figure 18

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2016/000120

A. CLASSIFICATION OF SUBJECT MATTER

G02B 5/20 (2006.01) G02B 5/28 (2006.01) G02B 6/10 (2006.01) G02B 6/24 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Databases: WPI, WPIAP and EPODOC. Keywords: G02B (CPC and IPC); filter, band pass, de-multiplex, G02B 5/20 (and sub-marks in CPC and IPC); waveguide, light guide, fiber optic, G02B 6/00 (and sub-marks in CPC and IPC); ring resonator; first, second, dual, pair, multiple, plural; frequency, wavelength, band, channel; input, incident, entrance; output, transmitted, exit; G02B 6/29335 (and sub-marks in CPC), G02B 6/29338 (and sub-marks in CPC), G02B 6/29389 (CPC), G02B 6/29361 (and sub-marks in CPC), G02B 2006/12109 (and sub-marks in CPC), G02B 2006/12164 (and sub-marks in CPC); AND LIKE TERMS. Database: Espacenet. Keywords: The University of Sydney (Applicant); Xiaoke Yi (Inventor), Shijie Song (Inventor), Suen Xin Chew (Inventor), Liwei Li (Inventor), Thomas Huang (Inventor); filter; G02B (IPC), G02B 6/-- (IPC); dual band; dual wavelength; ring resonator, ring, resonator; dual; SCISSOR. Database: Auspat. Keywords: The University of Sydney (Applicant); Xiaoke Yi (Inventor), Shijie Song (Inventor), Suen Xin Chew (Inventor), Liwei Li (Inventor), Thomas Huang (Inventor); filter; waveguide; dual. Database: Google Patents. Keywords: dual band; ring resonator; filter; waveguide; SCISSOR. Database: Google Scholar. Keywords: dual band; filter; waveguide; ring resonator; SCISSOR; Yi, Song, Chew, Li, Huang. Applicant and Inventor names searched in internal databases provided by IP Australia.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	

☒ Further documents are listed in the continuation of Box C

☒ See patent family annex

* "A"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		
Date of the actual completion of the international search 15 June 2016		Date of mailing of the international search report 15 June 2016	
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustalia.gov.au		Authorised officer Richard Baker AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262832583	

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/AU2016/000120
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7421168 B1 (GOUTZOULIS) 02 September 2008 column 2 lines 42 to column 3 line 37, column 4 line 56 to column 5 line 44, column 5 line 56 to column 6 line 3, figures 3, 9 and 11	1-3, 12-18, 20-25
X	US 7616850 B1 (WATTS et al.) 10 November 2009 column 3 line 26 to column 4 line 15, column 13 line 35 to column 14 line 21, column 15 lines 8 to 12, figure 5A	1-3, 12-18, 20

Form PCT/ISA/210 (fifth sheet) (July 2009)

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
the subject matter listed in Rule 39 on which, under Article 17(2)(a)(i), an international search is not required to be carried out, including
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

See Supplemental Box for Details

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-25

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

Supplemental Box**Continuation of: Box III**

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

This Authority has found that there are different inventions based on the following features that separate the claims into distinct groups:

- Claims 1 to 25 are directed to a dual band optical filter. The features of an input waveguide to input an optical signal; an output waveguide to output a filtered optical signal; a first filter path disposed between the input waveguide and the output waveguide and configured to couple a first frequency component of the optical signal to the output waveguide as a first band of the filtered optical signal; and a second filter path disposed between the input waveguide and the output waveguide and configured to couple a second frequency component of the optical signal to the output waveguide to form a second band of the filtered optical signal are specific to this group of claims.
- Claims 26 to 30 are directed to a photonic receiver. The features of a narrowband optical light source for emitting a first optical signal; a first optical modulator modulating the first optical signal in accordance with an externally received electromagnetic signal so as to produce a modulated optical signal; a series of optical resonator structures coupled to the modulated optical signal and outputting at least an optical sideband signal from the modulated optical signal are specific to this group of claims.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art.

When there is no special technical feature common to all the claimed inventions there is no unity of invention.

In the above groups of claims, the identified features may have the potential to make a contribution over the prior art but are not common to all the claimed inventions and therefore cannot provide the required technical relationship. Therefore there is no special technical feature common to all the claimed inventions and the requirements for unity of invention are consequently not satisfied *a priori*.

INTERNATIONAL SEARCH REPORT Information on patent family members		International application No. PCT/AU2016/000120	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
US 7421168 B1	02 September 2008	US 7421168 B1	02 Sep 2008
US 7616850 B1	10 November 2009	US 7616850 B1	10 Nov 2009
		US 7941014 B1	10 May 2011
		US 7983517 B1	19 Jul 2011
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001. Form PCT/ISA/210 (Family Annex)(July 2009)			