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(71) Applicant *(for all designated States except US)*: **LAMBDA CROSSING LTD.** [IL/IL]; 3 Shoham Street, North Industrial Park, P.O. Box 3028, 38900 Caesaria (IL).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **MARGALIT, Moti** [IL/IL]; 21 Hashita Street, 30900 Zichron Yaaqov (IL). **ORENSTEIN, Meir** [IL/IL]; 11 Yigal Alon Street, 32983 Haifa (IL).

(74) Agent: **REINHOLD COHN AND PARTNERS**; P.O. Box 4060, 61040 Tel-Aviv (IL).

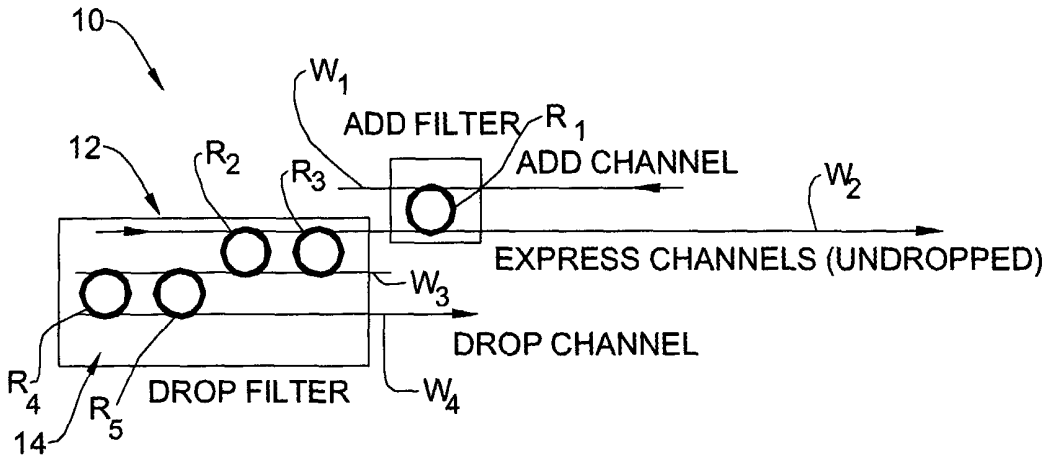
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(54) Title: RING WAVEGUIDE BASED OPTICAL DEVICE



(57) Abstract: An integrated optical device is presented. The device comprises at least one structure formed by three linear waveguides arranged in a spaced-apart parallel relationship, and two ring-like waveguides. One ring-like waveguide is located between the first and second linear waveguides being optically coupled to said first and second linear waveguides, and the other ring-like waveguide is located between the second and third linear waveguides being optically coupled to said second and first linear waveguides. This structure being is thereby operable as a single separation filter, when the first linear waveguide is connected to an input channel, and the third linear waveguide is connected to an output channel. By combining similar structures of the same configuration, a multiple-channel interleave filter can be obtained.

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Ring Waveguide Based Optical Devices

FIELD OF THE INVENTION

This invention is generally in the field of integrated optical devices and relates to optical devices utilizing ring-like waveguides.

BACKGROUND OF THE INVENTION

Optical communication is the enabling technology for the information age, and the essential backbone for long haul communication. As this technology progresses, there is a tremendous interest in providing optical routes in the short haul, metropolitan and access networks, as well as in local area networks and cable TV networks. In all these networks, the best of breed solution for bandwidth expansion has been the adoption of wavelength division multiplexing (WDM), which entails the aggregation of many different information carrying light streams on the same optical fiber.

Modern optical communications are based on transmitting frequency multiplexed optical signals in an optical fiber. An essential element in such systems is an optical add drop multiplexer (OADM), which can add or drop optical channels from an optical fiber. As shown in **Fig. 1**, an OADM is installed at the network's node, and is operable for selectively receiving laser-generated signals and allowing their propagation towards selective receivers.

Another important feature of optical communication systems is a frequency spacing between data channels. Interleaved filters are critical elements in achieving very tight frequency spaced optical channels. As shown in **Fig. 2A**, an interleave filter is operable to accept an input signal, which is composed of optical channels with a small frequency spacing, and distribute these input channels among output waveguides in a circular function. **Fig. 2B** illustrates the spectral functionality of the interleave filter. As shown, the output frequencies have a wider frequency spacing, as compared to that of the input frequency, resulting in wider tolerances from the optical elements.

Conventional approaches to interleave filters are based on low free spectral range filters. Such filters can be realized using Mach Zender interferometers realized in either fiber or waveguide, birefringent filter approaches (using polarization splitting), or low finesse Fabri Perot cavities.

Recently developed integrated electro-optical devices utilize ring resonators to achieve frequency selective switching. Such a device is disclosed, for example, in WO 99/17151. The device comprises a ring resonator interconnected by linear waviguides to couple light from first linear waveguide to the second one, when the frequency of the light passing through the first waveguide fulfils that of the resonance condition of the ring. The use of a switching mechanism providing de-tuning of a resonant ring out of resonance condition has been proposed, being disclosed for example in WO 98/53535.

SUMMARY OF THE INVENTION

There is accordingly a need in the art to improve the operation of electro-optical devices for use in optical communications, by providing a novel electro-optical device, such as an Optical Add Drop Multiplexer (OADM) or interleave filter, utilizing one- or multiple-ring resonator.

The optical device according to the present invention utilizes linear waveguides and ring-like waveguides (resonator) optically coupled to the linear

waveguides, and is capable of performing an add/drop multiplexing or interleave filtering function. The ring resonator(s) are interconnected by linear waveguides. Usually, this interconnection is realized by proximity coupling of the closed loop resonators to the linear waveguides. To achieve this, the closed loop resonators are placed in a relatively short distance away from the interconnecting waveguides.

The inventors have found that the use of a ring waveguide provides for a unique light coupling mechanism, which is facilitated by the ring resonator. Despite conventional wisdom, it has been found by the inventors that the use of a ring resonator enables to operate with higher differences between the refraction indices of a linear waveguide and a ring resonator coupled thereto. The conventional integrated optical devices typically employ a small refractive index difference between the waveguide region and the surrounding material. The reason for this is that the coupling of light strongly depends on the phase matching between the two waveguides. Such phase matching cannot be achieved over a large frequency range when the refractive index difference is greater then a few percent.

However, in the case of the ring resonator, the required amount of coupled light is small and can be achieved even for short distances and large refractive index differences. The phase matching permitting the transfer of a large amount of light is then facilitated by the ring structure.

Since optical waveguides can be implemented in a complex manner, the universal quantity characterizing the behavior of the confined light is the effective refractive index of the waveguide. In conventional passive devices, the difference between the effective refractive index of the waveguide and the index of the surrounding medium is typically smaller than 1%. When using ring-like micro-resonator structures (with small radius), the effective refractive index of the ring-like waveguide has to be relatively large, i.e., typically in the range of 10%-20% (depending on the ring diameter), to accommodate tight mode confinement and small losses. In these structures, however, the effective index of the ring waveguide and the linear waveguide are similar to within 3%. In an

integrated optical device according to the present invention, the refractive index of the ring waveguide is at least 20% greater than the refractive index of the linear waveguide that receives an input signal. For example, if the refraction index of a surrounding medium is 1.46, and the refraction index of a linear waveguide is 1.48, the refraction of a ring resonator coupled to the linear waveguide can be about 2 to provide successful operation of an integrated optical device.

The use of ring resonators is an ideal solution for implementing an interleave filter in a planar lightwave circuit, or an OADM. Additionally, the present invention takes advantage of the use of several (at least two) ring resonators between the two linear waveguides. This enables to utilize the collective response of one or more closed loop optical resonators (ring waveguides), which are connected to each other by two or more optical paths (linear waveguides), for filtering and add drop multiplexing.

There is thus provided according to one broad aspect of the present invention, an integrated optical device comprising at least one structure formed by three linear waveguides arranged in a spaced-apart parallel relationship, and two ring-like waveguides, one ring-like waveguide being located between the first and second linear waveguides and being optically coupled to said first and second linear waveguides, and the other ring-like waveguide being located between the second and third linear waveguides and being optically coupled to said second and first linear waveguides, said at least one structure being thereby operable as a single separation filter, when the first linear waveguide is connected to an input channel, and the third linear waveguide is connected to an output channel.

It should be understood that the terms ***"ring"*** or ***"ring-like"*** used herein signify any sufficiently smooth structure of a closed-loop or ring-like shape, such as elliptical shape, stadium-like shape, etc., and not necessarily a circular shape.

By providing additional similar structures accommodated between said structure and a corresponding number of output channels, a multiple-channel interleave filter can be constructed. This is implemented by optically connecting the first linear waveguides of all the structures to each other to define a common

first linear waveguide, interconnecting the common first linear waveguide between the input channel and one of the output channels, and connecting the third linear waveguides of all the structures to other output channels, respectively.

According to another broad aspect of the present invention, there is provided an integrated optical device operable as an optical add/drop multiplexer, the device comprising at least one structure formed by four linear waveguides arranged in a spaced-apart parallel relationship, thereby defining three pairs of linear waveguides, and by ring-like waveguides, each of the ring-like waveguides being located between the linear waveguides of the corresponding pair and being optically coupled to these linear waveguides, said optical add/drop multiplexer being realized by utilizing the first linear waveguide as an add channel and the fourth linear waveguide as a drop channel, the second linear waveguide thereby serving as an express channel.

At least one additional ring-like waveguide may be provided between the pair of linear waveguides so as to be optically coupled to these linear waveguides, the at least two ring-like waveguides between accommodated in a spaced-apart relationship in between the two linear waveguides.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, a preferred embodiment will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 is a block diagram of a conventional optical add/drop element;

Figs. 2A and 2B illustrate the operational principles of an interleave filter;

Figs. 3A-3C illustrate one-, two- and three-ring resonator filters, respectively, for use in OADM;

Fig. 4 graphically illustrates the spectral response of ring resonators of Figs. 3A-3C;

Figs. 5A and 5B illustrate main constructional features and main functional features, respectively, of a single-port Optical Add Drop Multiplexer (OADM) according to the invention;

Fig. 6 schematically illustrates a four-port OADM;

Fig. 7 schematically illustrates the integration of switches and add drop filters for switch-able filters;

Fig. 8 illustrates main components of a single separation filter according to the invention; and

Fig. 9 illustrates a four channel interleave filter according to the invention.

DETAILED DESCRIPTION OF THE INVENTION

Optical devices of the present invention are based on the use of optical ring resonators. Each ring resonator is an optical filter, and, by combining them in parallel, high order filters can be obtained.

Referring to Figs. **3A-3C**, basic filters of, respectively, one, two and three rings are illustrated. As shown, one or more ring waveguides $\mathbf{R_1}$, $\mathbf{R_2}$, $\mathbf{R_3}$ are accommodated between two linear waveguides $\mathbf{W_1}$ and $\mathbf{W_2}$, each ring waveguide being optically coupled to the respective linear waveguides.

The number of rings per functional filter may differ to accommodate the specifications of a particular optical network. This concept is illustrated in **Fig. 4** showing graphs $\mathbf{G_1}$, $\mathbf{G_2}$ and $\mathbf{G_3}$ corresponding to the optical spectral response of, respectively, one-, two- and three-resonator filters. The combination of two ring waveguides accommodated between and coupled to the two linear waveguides may be advantageously utilized in various optical devices.

Figs. 5A and 5B illustrate the main constructional features and main functional features, respectively, of a single channel OADM, generally designated **10**. The OADM **10** is composed of four linear waveguides $\mathbf{W_1}$-$\mathbf{W_4}$ located in a spaced-apart parallel relationship and ring waveguides (resonators) $\mathbf{R_1}$-$\mathbf{R_5}$. Ring resonator $\mathbf{R_1}$ is located between and coupled to the linear waveguides $\mathbf{W_1}$ and $\mathbf{W_2}$, ring resonators $\mathbf{R_2}$ and $\mathbf{R_3}$ are located in a spaced-apart relationship between linear

waveguides W_2 and W_3 being optically coupled thereto, and ring resonators R_4 and R_5 are located in a spaced-apart relationship between the linear waveguides W_3 and W_4 being optically coupled thereto. Waveguides W_2 and W_3 with two ring resonators R_2 and R_3, and waveguides W_3 and W_4 with two ring resonators R_4 and R_5 present two compound resonators **12** and **14**, respectively. Each such compound resonator presents a resonator-cavity loop functioning as a frequency-selective element. Here, each ring resonator is an optical filter, and, by combining them in parallel, high order filters are obtained. The drop port (filter) is implemented using the double filter pass, while the add port is obtained with the single filter.

Fig. 6 illustrates a four-port add/drop multiplexer. Here, multiple channel OADMs are obtained by cascading the structures of Fig. 5A-5B.

Fig. 7 illustrates an example of the integration of switches and add drop filters for switch-able filters. Here, optical switches are added to insert and extract the ring based OADM from the optical path.

Reference is now made to **Figs. 8 and 9** illustrating how an optical device of the present invention can be used as an interleave filter. As indicated above, interleave filters are typically employed to achieve tight channel spacing in optical communication systems.

Fig. 8 illustrates a single separation element (filter) **20** utilizing a ring resonator with a free spectral range (FSR), which is the frequency at which the response of an optical filter repeats itself and which is selected to be equal to the desired frequency spacing. The device **20** is composed of a ring resonator R_1 located between linear waveguides W_1 and W_2 being optically coupled to these waveguides, and a ring resonator R_2 located between waveguides W_2 and W_3 and being optically coupled thereto. As shown in Fig. 9, by combining three single stage filters **20A**, **20B** and **20C**, each constructed as the above-described device **20**, a four channel interleaved filter of Fig. 1 can be obtained. The combination of the filters 20A-20C is such that the first linear waveguides $W^{(A)}_1$, $W^{(B)}_2$ and $W^{(C)}_3$ are optically coupled to each other thereby defining a common linear waveguide W1

interconnected between an input channel, and linear waveguides $W^{(A)}_3$, $W^{(B)}_3$ and $W^{(C)}_3$ are connected to four output channels, respectively.

The integrated optical device according to the invention can be fabricated utilizing the vertical dimensions. Vertical fabrication tolerances are better than horizontal tolerances, and therefore such a vertical integrated optical device is simpler or cheaper to manufacture. The vertical dimension, which is easier to control in conventional processes, can mediate the structure for accurate coupling.

Those skilled in the art will readily appreciate that various modification and changes can be applied to the embodiments of the invention as hereinbefore exemplified without departing from its scope defined in and by the appended claims.

CLAIMS:

1. An integrated optical device comprising at least one structure formed by three linear waveguides arranged in a spaced-apart parallel relationship, and two ring-like waveguides, one ring-like waveguide being located between the first and second linear waveguides and being optically coupled to said first and second linear waveguides, and the other ring-like waveguide being located between the second and third linear waveguides and being optically coupled to said second and first linear waveguides, said at least one structure being thereby operable as a single separation filter, when the first linear waveguide is connected to an input channel, and the third linear waveguide is connected to an output channel.

2. The device according to Claim 1, and also comprising additional similar structures accommodated between said structure and a corresponding number of output channels, the first linear waveguides of all the structures being optically connected to each other to define a common first linear waveguide, the device being thereby operable as a multiple-channel interleave filter, when said common first linear waveguide is interconnected between the input channel and one of the output channels, and the third linear waveguides of all the structures are connected to other output channels, respectively.

3. The device according to Claim 1, wherein said structure also comprises an additional linear waveguide, the four linear waveguides being accommodated in the spaced-apart parallel relationship, and at least one additional ring-like waveguide located between the third and fourth linear waveguides being optically coupled thereto, the device being thereby operable as an optical add/drop multiplexer by utilizing the first linear waveguide as an add channel and the fourth linear waveguide as a drop channel, the second linear waveguide thereby serving as an express channel.

4. The device according to Claim 3, wherein said structure comprises at least one additional ring-like waveguide accommodated in a spaced-apart relationship with the ring-like waveguide located between the second and third linear

waveguides and being optically coupled to these linear waveguides, said second and third linear waveguides and the ring-like waveguides between them presenting a closed loop compound resonator.

5. The device according to Claim 3 or 4, wherein said structure also comprises at least one additional ring-like waveguide accommodated in a spaced-apart relationship with the ring-like waveguide located between the third and fourth linear waveguides and being optically coupled to these linear waveguides, said third and fourth linear waveguides and the ring-like waveguides between them presenting a closed loop compound resonator.

6. The device according to Claim 4 or 5, wherein the refractive index of each of the spaced-apart ring-like waveguides is at least 20% greater than the refractive index of the linear waveguide optically coupled to said ring-like waveguides.

7. The device according to any one of Claims 3-6, and also comprising additional similar structures accommodated in cascade-like arrangement, such that the drop channel linear waveguide of one structure is optically coupled to the add channel linear waveguide of the successive structure, the device being thereby operable as a multiple channel OADM.

8. An integrated optical device operable as a multiple-channel interleave filter, the device comprising several structures, each formed by three linear waveguides arranged in a spaced-apart parallel relationship and two ring-like waveguides, one ring-like waveguide being located between the first and second linear waveguides and being optically coupled to said first and second linear waveguides, and the other ring-like waveguide being located between the second and third linear waveguides and being optically coupled to said second and first linear waveguides,. the first linear waveguides of all the structures being optically connected to each other to define a common first linear waveguide interconnectable between an input channel and one of output channels, and the third linear waveguides of all the structures being connectable to other output channels, respectively.

9. An integrated optical device operable as an optical add/drop multiplexer, the device comprising at least one structure formed by four linear waveguides arranged in a spaced-apart parallel relationship, thereby defining three pairs of linear waveguides, and by ring-like waveguides, each of the ring-like waveguides being located between the linear waveguides of the corresponding pair and being optically coupled to these linear waveguides, said optical add/drop multiplexer being realized by utilizing the first linear waveguide as an add channel and the fourth linear waveguide as a drop channel, the second linear waveguide thereby serving as an express channel.

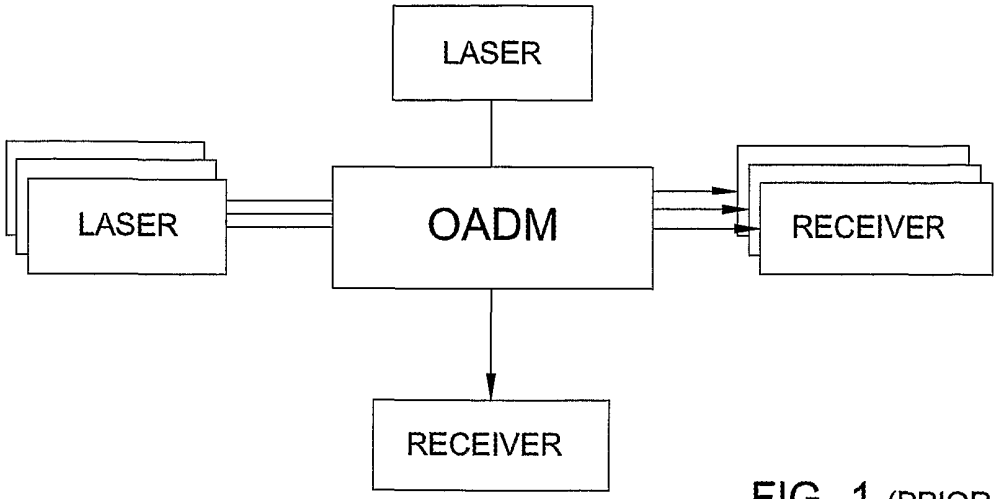


FIG. 1 (PRIOR ART)

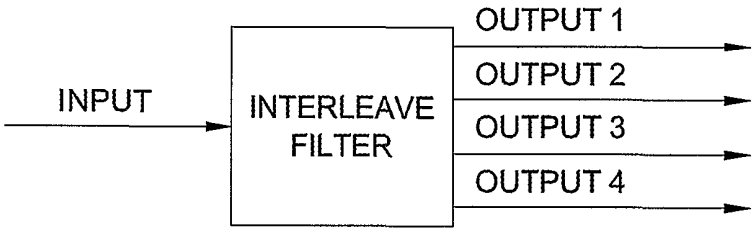


FIG. 2A (PRIOR ART)

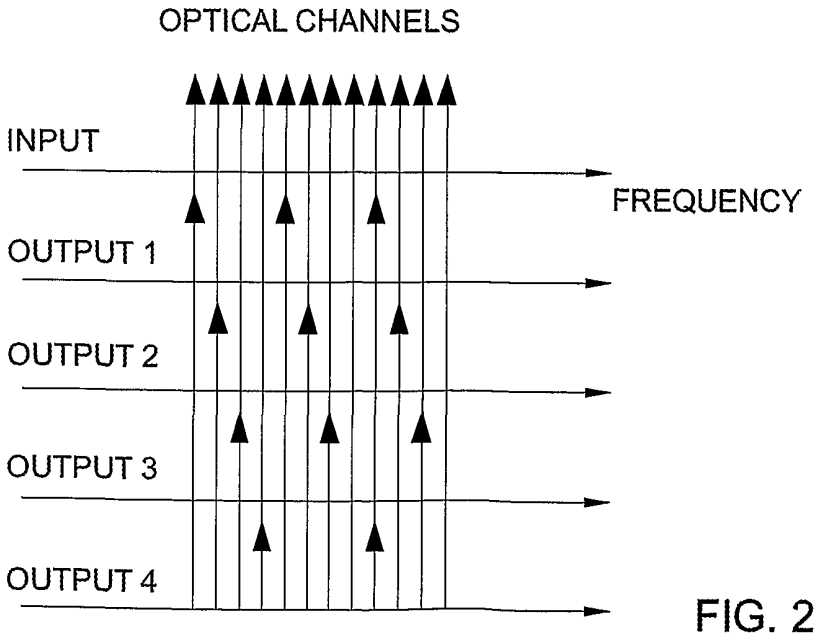


FIG. 2B (PRIOR ART)

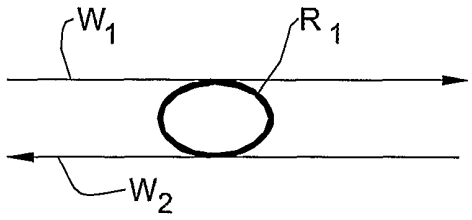


FIG. 3A

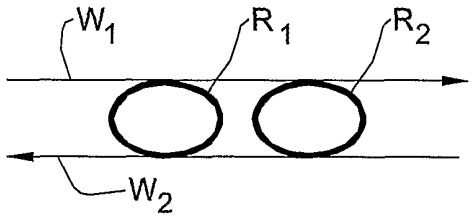


FIG. 3B

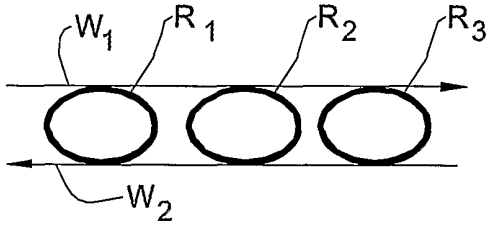


FIG. 3C

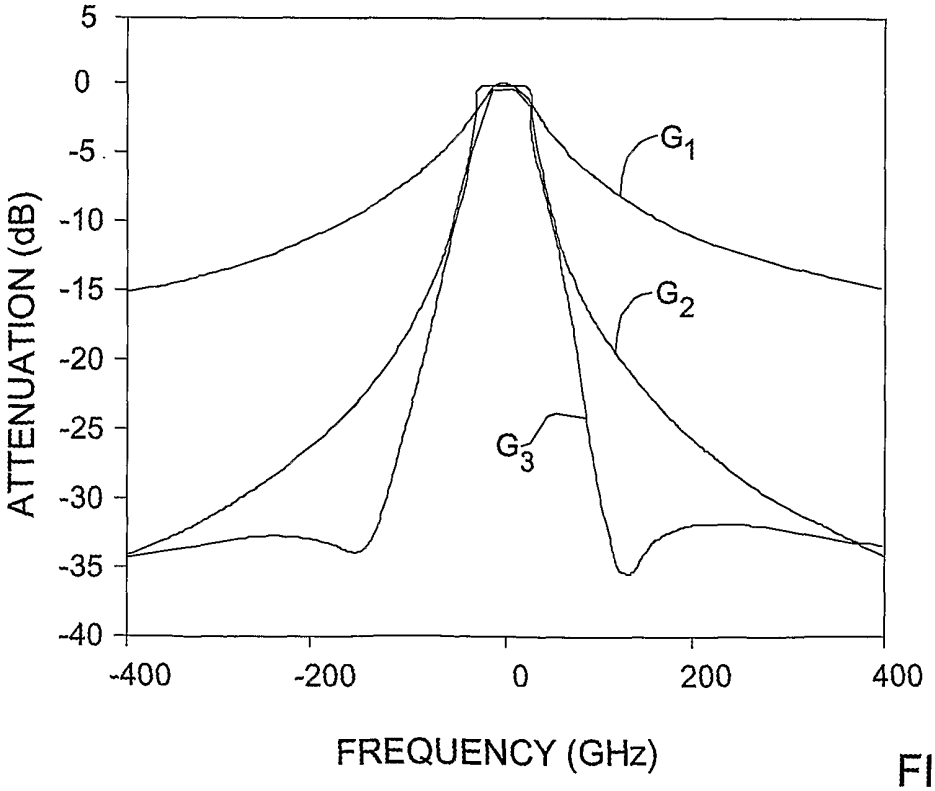


FIG. 4

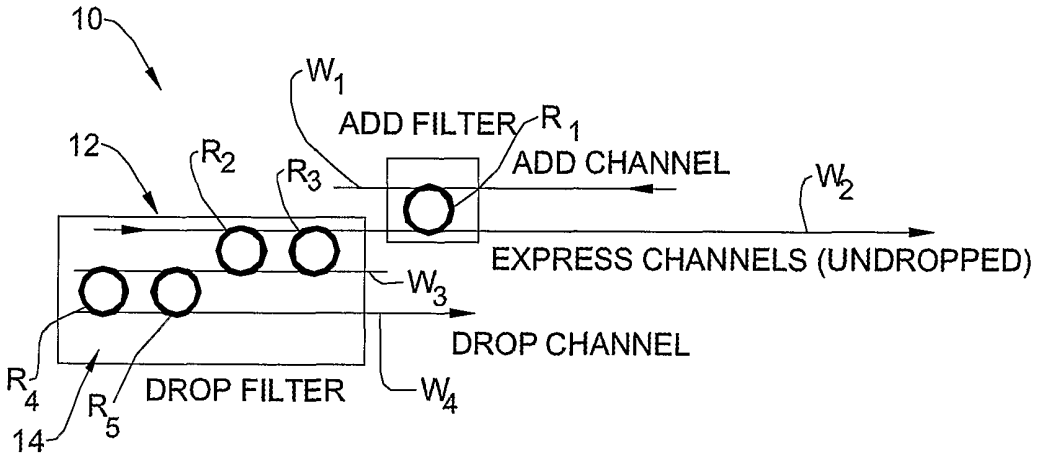


FIG. 5A

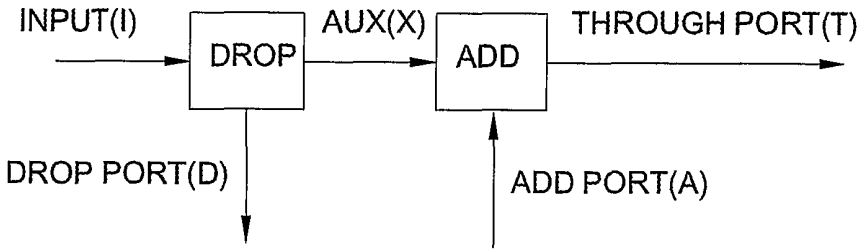


FIG.5B

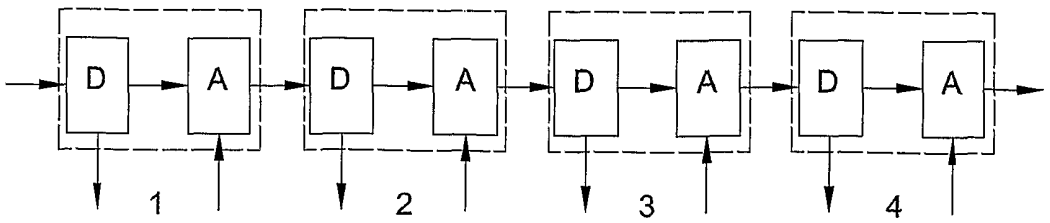


FIG. 6

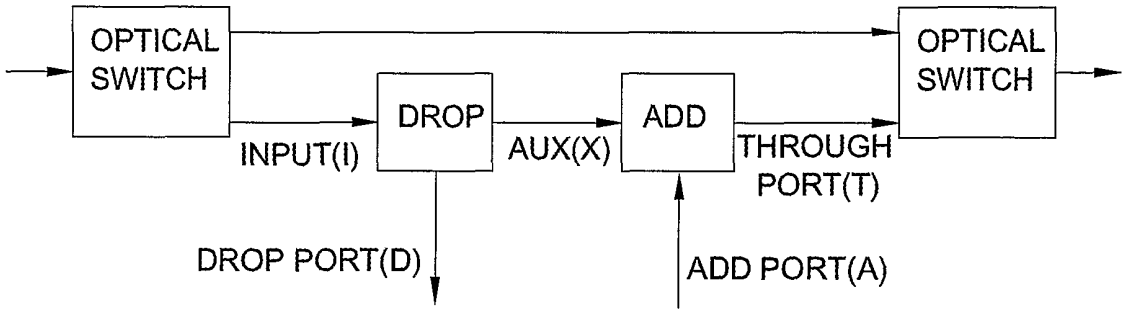


FIG. 7

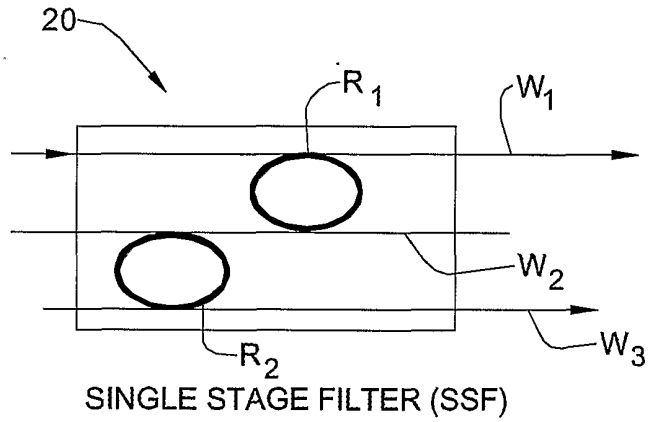


FIG. 8

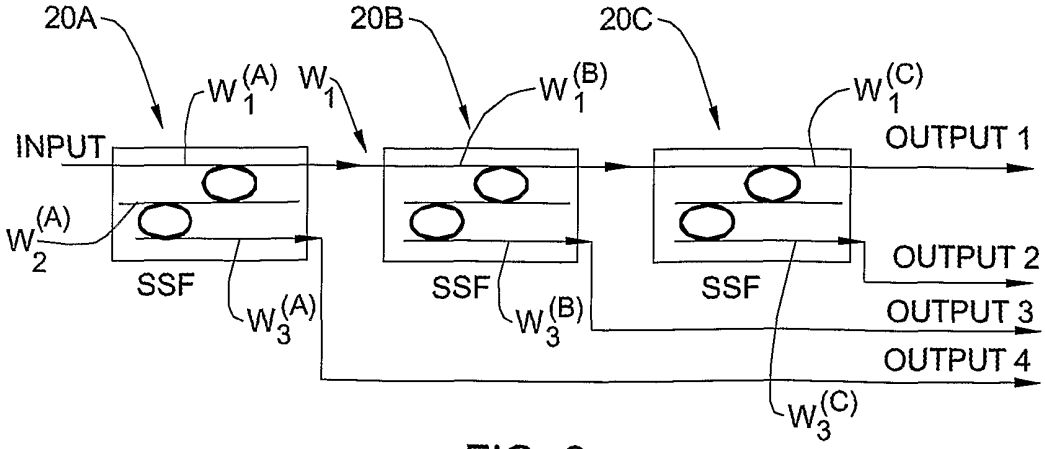


FIG. 9