(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
6 July 2006 (06.07.2006)

PCT

(10) International Publication Number
WO 2006/069789 A2

(51) International Patent Classification:
G02B 6/293 (2006.01)

(21) International Application Number:
PCT/EP2005/014109

(22) International Filing Date:
29 December 2005 (29.12.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
04031005.4 30 December 2004 (30.12.2004) EP

(71) Applicant *(for all designated States except US)*: **PROXIMION FIBER SYSTEMS AB** [SE/SE]; Skalholtsgatan 10B, S-164 40 Kista (SE).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **SAHLGREN, Bengt** [SE/SE]; Norrholmsvägen 92, S-132 31 Saltsjö-Boo (SE). **STUBBE, Raoul** [SE/SE]; Sommarvägen 5, S-182 74 Stocksund (SE). **BERGMAN, Mikael** [SE/SE]; Odalslingan 38, S-175 43 Järfälla (SE). **HELMFRID, Sten** [SE/SE]; Köpenhamnsgatan 24, S-164 42 Kista (SE). **PEJNEFORS, Johan** [SE/SE]; Näckrosvägen 27, 2tr, S-169 37 Solna (SE). **JOHANSSON, Bengt** [SE/SE]; Naumannsvägen 19, S-129 38 Hägersten (SE).

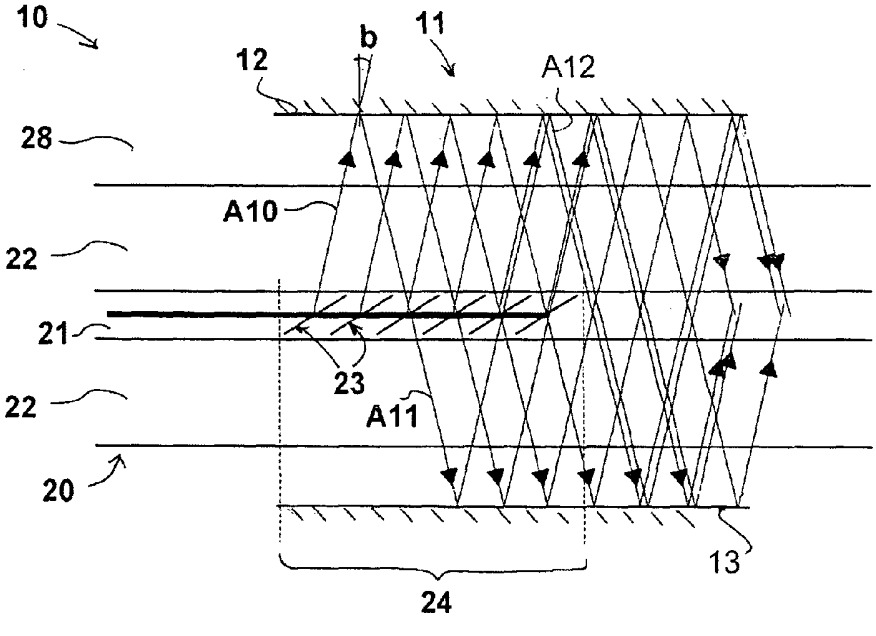
(74) Agent: AWAPATENT AB; Box 45086, S-104 30 Stockholm (SE).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: OPTICAL COUPLER



(57) Abstract: The invention is a spectrally selective optical coupler with a new geometry and a new principle of action. An optical coupler according to the invention comprises an optical fiber and an external light guide. In the fiber there is provided a deflector that is operative to deflect light of a predetermined wavelength into a bound, propagating mode of said light guide. The outcoupled light is guided to a region remote from the outcoupling portion of the fiber. The invention can be used to couple light from a first to a second optical fiber.

Published:

— *without international search report and to be republished upon receipt of that report*

OPTICAL COUPLER

Technical field

The present invention relates to a spectrally selective optical coupler of the type where light is coupled transversally to and from an optical waveguide, such as an optical fiber.

Technical background

Spectrally selective optical couplers, also known as channel drop or add filters, are utilized for extraction of a single wavelength channel from a broadband optical signal, or for insertion of a single wavelength channel into a broadband optical signal. Typically, spectrally selective couplers are used in wavelength division multiplexed (WDM) optical communications systems for adding and dropping a single wavelength channel.

Channel drop filters have previously been implemented as dual-waveguide couplers. The article "Narrow-Band Optical Channel-Dropping Filter", Journal of Lightwave Technology, vol. 10, no. 1, January 1992 (Haus et al.) describes an optical channel-dropping filter comprising a first and a second waveguide, the first of which contains a $\lambda/4$ shifted distributed feedback (DFB) resonator. Light propagating in the second waveguide is coupled to the first waveguide by evanescent coupling between the two waveguides. Only one wavelength of light is resonant in the first waveguide, and consequently only that wavelength of light is efficiently coupled to the first waveguide. By making the $\lambda/4$ shifted DFB resonator asymmetric (i.e. the grating is longer on one side of the $\lambda/4$ shift), light can be coupled out of the DFB resonator.

However, prior art channel drop filters have some significant drawbacks and limitations. The filters are difficult to manufacture, due to the fact that very precise placement of the waveguides is required in order to obtain a reliable evanescent coupling. Furthermore, the prior art filters are difficult to control and tune. The coupling strength and the coupled wavelength is, to a large extent, fixed once the device has been assembled. Also, each filter needs to be of a certain size in order for the desired discrimination to be achieved. In particular, when a number of channels are to be dropped separately (e.g. when constructing a demultiplexer), the device needs to be quite large. Yet another problem with the prior art filters is that they are difficult to implement in a fiber configuration, since the evanescent coupling between the waveguides needs to be very accurate. Any perturbation of either of the waveguides can cause large uncontrolled changes in performance.

WO 02/06878 discloses a spectrally selective coupler having a new geometry and a new principle of action compared to yet earlier couplers. It is proposed in that publication to couple light transversally out from an optical fiber by means of a deflector in the form of blazed optical Bragg gratings. Light is coupled transversally from the fiber into an external resonator of the Fabry-Perot type. The light wavelength that is resonant in the external resonator is more strongly coupled to and from the optical fiber. By altering the properties of the external resonator, such as the distance between the reflecting surfaces, the wavelength to be coupled can be tuned.

Although the technology disclosed in WO 02/06878 provided some important improvements over the yet earlier art, some problems still remain. The technology has an inherent geometrical problem, in that the separation between the mirrors of the external resonator must be about 20 µm or less in order to allow convenient tuning. A larger separation gives a shorter free spectral range (FSR), and hence a smaller separation between the resonant wavelengths. As will be appreciated, there is a lower limit for the FSR below which it will be difficult to separate wavelength channels. With the above-described art, it turns out to be difficult to arrange two optical fibers within the same external resonator, when coupling from one fiber to another is to be accomplished, given the desire to have a sufficiently large FSR (i.e. a sufficiently small separation between resonator mirrors). This is not only due to the limited space between the reflected surfaces of the resonator, but also due to the fact that both fibers have to be accurately positioned inside the resonator with respect to the two reflective surfaces of the resonator. Moreover, since the resonant mode of the external resonator overlaps spatially with the deflector in each optical fiber, there will be interactions between the light in the external resonator and the light still confined to the core of the fiber. These interactions might disturb the confined light, which propagates inside the core of the fiber.

Summary of the invention

Therefore, it is a general object of the present invention to provide an improvement of the art described above. In particular, it is an object of the present invention to address the geometrical problem of transverse coupling of light to and from a waveguide, as well as the problem of remnant interaction between light in the external resonator and the light in the waveguide.

The term "transverse" for describing the coupling of light to and from an optical waveguide, such as an optical fiber, as used herein, means that the light is coupled in a non-axial direction with respect to the fiber axis, typically through the fiber cladding. In order to accomplish transverse coupling of light, there is typically required some kind of deflector in the optical waveguide for changing the propagation direction of the light into a transverse (i.e. non-axial) propagation direction.

Such improvement is obtained by an optical coupler as defined in the appended claims.

The present invention is based upon the insight that if light, which is transversally coupled out from an optical fiber, is guided away from the deflecting portion of the fiber, handling and manipulation of the outcoupled light will be facilitated. In other words, when the outcoupled light is transported or guided away from the deflecting portion of the fiber, the interaction between the outcoupled light and light remaining in the fiber is eliminated or at least substantially reduced. Hence, a more versatile handling of the outcoupled light is facilitated, while the light remaining inside the core of the fiber is left substantially unperturbed.

The present invention provides a spectrally selective optical coupler, which comprises a first optical fiber having a core and a cladding. In said fiber there is provided a deflector for deflecting at least some of the light propagating in said fiber core. The deflector is arranged such that the light is deflected out from the fiber transversally under an angle that avoids total internal reflection between the fiber cladding and an outer medium surrounding said cladding (and preferably being substantially index matched therewith). Further, an external light guide, which is defined by at least a first and a second reflecting surface, is arranged in said outer medium. The optical fiber is arranged between said first and said second reflective surface of the light guide. In particular, the deflector is arranged to deflect light propagating in said fiber into a bound, propagating mode of the external light guide. The wavelength of light entering the bound, propagating mode will correspond to one or more of the allowed modes of the external light guide, e.g. as determined by the distance between said reflectors. In this context, a bound, propagating mode of the external light guide corresponds to light, which is not merely reflected between the same two surface portions such as in a conventional etalon, but rather transported continuously further in space.

Light will be deflected out from the fiber into the surrounding medium at different angles, which are determined *inter alia* by the wavelength of the light in relation to the grating period, and the inclination of the Bragg grating in relation to the propagation axis in the fiber, as is known in the art. Hence, different wavelengths will typically be deflected in slightly different directions. It is possible to arrange the outcoupling angle for the light such that the light will have a propagation vector parallel to the fiber inside the external light guide. By adjusting the separation between the mirrors of the external light guide, the free spectral range FSR of the light guide can be altered. The FSR determines the separation between the wavelengths of propagation modes in the light guide. By making the FSR of the light guide sufficiently large, e.g. by making the separation between the mirrors small, only one of the outcoupled wavelengths will, for the relevant deflection angles, be able to propagate inside the light guide with a propagation vector component parallel to the fiber axis (i.e. in a bound, propagating mode). This wavelength may be called the resonant wavelength of the light guide.

In order to facilitate adjustment of the separation between the mirrors, the outer medium surrounding the fiber cladding could be divided into an index matched medium close to and surrounding the fiber, and a gap next to one of the mirrors. In this context, the surface of the index matching medium is preferably substantially parallel to the fiber core.

It should be noted that the light that is transported by the external light guide will undergo a large number of reflections between the mirrors of this light guide. Thus, the reflectivity of the mirrors defining the external light guide should be very high, preferably more than 99%. Therefore, it is preferred to use dielectric mirrors for the external light guide. Moreover, since light will pass the fiber core and cladding in a transverse direction at the deflecting portion of the fiber, it is preferred to let the transition of the refractive index between the cladding and the core be smooth (i.e. not step-wise), thereby reducing scattering of light when passing between the core and the cladding.

Preferably, a blazed Bragg grating is used for deflecting the light out from (and into) the fiber core. Even more preferred is to use an apodized blazed Bragg grating. The apodized grating may advantageously have the properties of a band pass filter. The transform into the spatial domain of an ideal band pass filter leads to a sinc-like function. Normally, only a modified portion of the sinc-like function is used, as there is often a desire to keep the length of the deflection grating as short as possible. This can be implemented by breaking off the sinc-like function after the two first side lobes, such that only one side lobe on each side of the main lobe remains. Conclusively, the use of an apodized Bragg grating gives a good suppression of distortions for a wide wavelength range.

Preferably, the separation between the mirrors of the external light guide is controllable, e.g. by electrostatic tuning or otherwise. There are at least three advantages related to an optical coupler with tuneable mirrors. Firstly, the same type of optical coupler can be used for controlling several different wavelengths. Hence, fewer components are needed. Secondly, the exact final performance and operation of the optical system need not be determined when the system is assembled, as the resonant wavelength of each respective optical coupler can be tuned afterwards. Thirdly, it is possible to reconfigure such an optical system with regard to a change in the routing of different wavelength channels.

A more improved tuning of the resonant wavelength can be achieved, if at least one of said two mirrors of the external light guide is functionally divided into several reflective sub sections, wherein each sub section is individually controllable with respect to its distance to and/or orientation in respect to the second opposing mirror of said light guide. In this way, each sub section or sub mirror may, for example, be arranged and tuned such that it compensates for various imperfections of the external light guide. In general, it is highly advisable that discrete mirror elements are avoided when utilizing sub mirrors according to above. Rather, the light guide mirrors should preferably appear as continuous elements, which are separately controllable in smaller, confined regions. In other words, the sub sections, or sub mirrors, are preferably defined by way of portion-wise controllability, rather than by discrete mirror sections.

In many applications there is a desire to switch the outcoupling of a certain wavelength on and off, without disturbing the other wavelengths, e.g. in channel add drop applications. One way of achieving this is to incorporate double, superimposed blazed gratings at the deflecting portion. A wavelength of light is then transversally decoupled both "upwards" and "downwards" (outcoupled light and fiber core are typically in a common plane). This wavelength interferes constructively if both mirrors are in the resonant position. By moving the two mirrors "downwards" or "upwards" by e.g. a quarter of a wavelength, this will cause the outcoupled wavelength to interfere destructively, i.e. the drop function of the optical coupler will be switched off. The mirrors should in this case preferably be moved simultaneously or in small steps in order for the light not to interfere with other channels.

There is also a desire to be able to switch from one channel to another without disturbing any other channels, i.e. switch from one propagating wavelength to another in the external light guide without scanning through any intermediate wavelengths, so called hitless tuning. This can be achieved if, before the separation between the mirrors of the external light guide is adjusted to fit the new resonant wavelength, the mirrors are arranged, or detuned, such that the outcoupled light from the fiber is temporarily unable to propagate in the external light guide, effectively eliminating any bound, propagating modes. For example, one of the reflective surfaces of the light guide may initially be rotated or tilted, preferably such that the separation distance is decreased between the reflective surfaces at a first end of the waveguide, and increased at the other end of the waveguide. Consequently, no light will propagate in the light guide and the difference in mirror separation preferably corresponds approximately one FSR between said first and second end of the light guide. Thereafter, the tilted reflective surface is rotated back, such that the two reflective surfaces are again in parallel with each other. For the latter rotation, the axis of rotation is suitably chosen such that the new separation distance between the reflective surfaces corresponds to the new desired propagating wavelength.

Alternatively, an absorbing section may be introduced in the light path of the external light guide. While the external light guide is in this non-resonant condition, the separation between the mirrors in the external light guide is adjusted to correspond to the new resonant wavelength, before the absorbing section is removed. This may be implemented, for example, by means of a fixed section that can be switched between absorbing and non-absorbing states.

Advantageously, the outcoupled light may be guided by said light guide to a region which is remote from said first optical fiber and/or from the deflecting portion thereof. In this way, the light is prevented from interacting with this fiber, and at the same time the handling and manipulation of the light is facilitated. Further, the ability of guiding the light away from the fiber gives many options when it comes to the design of the optical coupler, as the outcoupled light can be handled and manipulated with a large degree of freedom.

In one embodiment of the invention, light is coupled out from a first optical fiber, and at least some of the outcoupled light is later coupled into a second optical fiber or back into the first optical fiber. When the light is coupled back into the first optical fiber, the light can either be coupled back at the same portion of the fiber where it was coupled out, or it can be coupled back at a different portion of the fiber.

The outcoupled light may be guided by the external light guide in a direction parallel to the core of the fiber. The light guide may be terminated by a retro-reflector downstream of the deflecting portion of the fiber. Consequently, the light may be guided back towards the deflecting portion of the fiber, where it may be coupled into the core of the fiber in a direction opposite to the one it had before it was coupled out. The retro-reflector can conveniently be implemented by making the reflecting surfaces of the external light guide slightly inward-slanting (i.e. towards the fiber), such that the propagation direction for the mode within this light guide is reversed. Again, the resonant wavelength of the light guide may be tuneable in a convenient manner. The tuneability will typically be equal to the FSR.

In a different embodiment of the invention the light may be coupled out from an optical fiber, without being coupled back into the same fiber or into another fiber. Instead the light may simply dropped, or if desired it can be analyzed or otherwise manipulated.

By bringing the light away from the portion of the fiber containing the deflector, more degrees of freedom are introduced when it comes to handling and manipulating the light. Once the outcoupled light has propagated beyond the fiber deflection portion as a bound, propagating mode of the external light guide, interaction between the outcoupled light and the light remaining in the fiber is eliminated. This outcoupled light may thus be manipulated without interfering with light in the fiber.

Advantageously, the external light guide may comprise a first, a second and a third light guiding portion. These portions can be arranged as separate devices, but are preferably joined to each other in order to facilitate the arrangement of the fibers. The first light guiding portion is arranged to guide outcoupled light from a first deflecting portion of the fiber towards said second light guiding portion, preferably along the light propagation axis of the fiber, until the light within said first portion reaches beyond said first deflecting portion. Said second light guiding portion is arranged to receive light from said first light guiding portion and to guide said light towards said third light guiding portion. Said third light guiding portion is arranged to receive light from said second light guiding portion and to couple said light into a second optical fiber. The incoupling of the light into the second fiber works in principle as a time reversal of the outcoupling of the light from the first fiber. Again, although described as having a first, a second and a third portion, the external light guide is preferably implemented as a continuous element.

Advantageously, the transfer of the received light by said second light guiding portion is performed either by waveguiding or by lens action. If waveguiding is used, the received light is bound in a mode of said second light guiding portion (e.g. between two reflective surfaces). On the other hand, if lens action is used, the received light is directly mirrored, by e.g. an elliptical reflective surface of said second light guiding portion, to a receiving portion of said third light guiding portion. When waveguiding action is used, preferably at least one of the reflecting surfaces is curved in a dimension non-parallel to the propagation axis of said light guide, such that light is more easily confined to a bound mode therein.

Advantageously, when the deflector and/or the external light guide is highly polarization dependent, an additional external light guide arrangement can be used. This additional arrangement is preferably arranged similar to said first light guide arrangement, but is rotated 90 degrees around the axis of said first fiber, compared to said first arrangement in order to handle the orthogonal polarization direction.

In order to make sure that a desired wavelength is completely dropped, a band-stop filter or a reflecting filter may be arranged after the deflecting portion(s) of the fiber, i.e. downstream from the deflector, in the propagation direction of the light which is to be dropped.

Brief description of the drawings

In the following, preferred embodiments of the present invention will be described in more detail. The various objects and advantages of the invention will be appreciated when the detailed description is read in conjunction with the accompanying drawings.

Figure 1 schematically illustrates the principal operation of a device according to the invention.

Figure 2 schematically illustrates how outcoupled light may be manipulated and coupled back into the fiber.

Figure 3 schematically shows how light may be coupled out of a first optical fiber and into a second optical fiber according to a first embodiment of the invention.

Figure 4 schematically shows how light may be coupled from a first fiber to a second fiber by an optical coupler according to a second embodiment of the invention.

Figure 5 schematically shows how a first and a second polarization direction of the light may be coupled by a first and a second optical coupler, respectively, from a first optical fiber to a second optical fiber.

In the figures, like parts are designated by like reference numerals.

Detailed description of the invention

In figure 1, a wavelength selective optical coupler 10 is shown comprising an optical fiber 20 and an external light guide 11. The optical fiber comprises a core 21, a cladding 22 and a deflector 23. The deflector is comprised of an optical Bragg grating. The optical Bragg grating 23 is blazed (i.e. tilted) with respect to the fiber core, in the sense that boundaries between domains of the Bragg grating are non-parallel to the electromagnetic field of light propagating in the fiber. The deflector 23 is operative to deflect light propagating in the core 21 of the optical fiber 20 into said external light guide 11. The light guide 11 is defined by a first mirror 12 and a second mirror 13, which are arranged on opposite sides outside said fiber 20. In this preferred embodiment, the mirrors 12 and 13 are essentially parallel to the fiber core, thereby defining a light guide in which a resonant wavelength of the deflected light will propagate along the fiber. Whether light that is propagating in the fiber core is deflected by the Bragg grating or not is determined by e.g. the wavelength of the propagating light, and the angle of inclination of the grating (its blaze angle) in relation to the fiber core axis.

The angle at which the light is coupled out from the fiber, into the surrounding medium 28, is determined by the wavelength of the propagating light with respect to the grating period, the angle of inclination of the grating, and the index of refraction in the fiber cladding, the fiber core and the surrounding medium. The deflector can be arranged to deflect essentially all wavelengths propagating in the core into the external light guide. In this case, the free spectral range of the external light guide 11 is preferably larger than the entire wavelength range of the optical signals at issue, in order to ensure that only one wavelength channel will propagate in a bound mode of the external light guide 11. Care should be taken when arranging the fiber, such that the desired outcoupled wavelength corresponds to, and is coupled into, a mode which is able to propagate inside the external light guide 11, i.e. a bound, propagating mode. As can be seen in Figure 1, the light is coupled out into the index matched surrounding medium 28 at an angle b, with respect to a transversal direction from the fiber. The angle b is chosen such that light of a desired wavelength will enter a bound, propagating mode in the light guide 11.

The choice of angle b is an optimization between the length of the device and the wavelength selectivity on one hand and the FSR and the sensitivity to reflector imperfections on the other hand. For the same distance between the reflectors defining the external light guide a larger angle b means a larger FSR, but the wavelength selectivity decreases for large angles unless the deflector section is made very long. Preferably, the angle b is between 5 and 15 degrees.

Only a small portion of the light is coupled out at each grating element. Therefore, the grating should be made sufficiently long, such that a desired amount of light is coupled out. Arrows A10, A11, A12 indicate the propagation direction of the light. As will be understood, since the propagation of light is time invariant, the deflector 23 is also operative to deflect light propagating inside said light guide 11 into the fiber 20 and the fiber core 21. Once the light has been guided by the mirrors 12 and 13 away from the deflecting portion 24 of the fiber, i.e. to a region beyond the longitudinal extension of the fiber comprising the deflector, the interaction of the outcoupled light with the light remaining in the fiber is essentially eliminated. Hence, beyond the deflecting region 24, the outcoupled light may be manipulated, substantially without affecting light remaining in the fiber.

A second embodiment of the invention is schematically shown in Figure 2. In this embodiment, the first mirror 12 of said external light guide comprises several sub mirrors 210-218, wherein each of these sub mirrors can be controlled individually with respect to their orientation and position. It should be emphasized that these sub mirrors do not typically comprise individual, discrete elements. Rather, the sub mirrors are advantageously defined as individually controllable regions of a larger, continuous mirror surface, as mentioned above. Manufacturing a large mirror with ideal properties, e.g. absolutely flat, is difficult and it is even harder to make a working pair of mirrors. Therefore, in this embodiment, one of the mirrors is divided into a set of sub-mirrors 210-218 by providing regions of mirror 12 with individual controllability. By arranging each of these sub mirrors in a respective ideal position and orientation, a more optimized light guide can be achieved. The outcoupling of the light and the guidance of said light works in essentially the same way in this embodiment as was described in relation to figure 1. In Figure 2, further schematic arrows are used for indicating the propagation of the light. Arrow A21 indicates the propagation direction of the light in the core of the fiber. Arrow A22 indicates the direction in which the light is coupled out of the fiber. Arrow A23 indicates the initial propagation direction of said outcoupled light; this direction is the same as is illustrated by the arrows A10-A13 in Figure 1.

In Figure 2 the outcoupled light is shown to be reflected after it has interacted with a modulator 14, and is guided back towards the deflecting portion 24 of said fiber. The optical modulator can thus be arranged as a wavelength selective modulator, since it can be made to operate only on the light coupled to the bound, propagating mode of the external light guide. When the light again reaches the deflecting portion 24 it is coupled back into the fiber by the deflector 23 to propagate in the core of the fiber in an opposite direction. Hence, this direction is opposite to the propagation direction the light had before it was coupled out of the core of the fiber.

It should be understood, however, that the principle of sub mirrors as described above may be used with or without any modulator 14, the embodiment shown in the figure merely being one example amongst many.

Figure 3 schematically shows an embodiment of the present invention wherein one wavelength channel λ_m is dropped from a first optical fiber 20 and added to a second optical fiber 30. The two optical fibers 20 and 30 are arranged a small distance apart, typically in the order of tens of microns, and parallel to each other. Said first optical fiber 20 and a first light guiding portion 31 of the external light guide are arranged in accordance with what has been described in relation to Figure 1. Light corresponding to several wavelength channels $\lambda_1,\ldots,\lambda_m,\lambda_n$ may propagate inside the core of said first fiber in a direction which is illustrated by an arrow A31. At the deflection portion 24, light to which said first portion of the external light guide is resonant is coupled out from said first fiber 20 and into said first light guiding portion 31 as described above, where it propagates towards a second light guiding portion 41 along the propagation axis of said first fiber 20, as indicated by arrow A32. The second light guiding portion 41 receives the propagating light, from said first light guiding portion 31, after the light has passed beyond the deflection portion 24, and guides it towards said second fiber 30 and a third light guiding portion 51. The propagation direction in said second light guiding portion 41 is, in this embodiment, substantially orthogonal to said first propagation direction A31, as illustrated by arrow A33. When the light reaches said third light guiding portion 51, it is guided by it along a deflection portion 34 of said second fiber, as is indicated by an arrow A34. At the deflection portion 34 of the second fiber, the propagating light is coupled into said second fiber 30, in a way which may be seen as a time reversal of the outcoupling of light from said first fiber 20. The light coupled into the second fiber then propagates along the core of said second fiber as indicated by arrow A35.

By cooperation between the deflecting portions 24, 34 and the bound modes of the external light guide, one desired wavelength channel λ_m can be coupled over between the fibers, while remaining channels continue substantially unaffected in the original fiber.

Figure 4 schematically illustrates a further embodiment, wherein light is coupled from the first optical fiber 20 to the second optical fiber 30 in accordance with the invention. This embodiment is designed in a similar manner as the embodiment shown in Figure 3, except that another design of the second light guiding portion 41 is used. The second light guiding portion comprises a first mirror 42 and a second mirror 43. Here, the second light guiding portion does not direct the propagating light orthogonal to the propagation axes of the fibers. Rather, the propagation direction of the outcoupled light is gradually changed, beginning at a point after the deflection portion 24 of the first fiber 20, where it propagates in a direction parallel to the first fiber core, and ending at a point before the deflection portion 34 of said second fiber, where the light propagates parallel to said second fiber. "Before" and "after" are here related to the propagation direction of the outcoupled light, i.e. upstream and downstream. Preferably, one of the mirrors 41 has a radius of curvature of between 50 and 500 µm, in order to ensure a better control of the light within the external light guide. Further, the whole upper reflective surface of the light guide might be formed in one continuous piece; in other words, an upper light guiding unit comprising the upper reflective surface of said first, second and third light guiding portion. Correspondingly, a lower light guiding unit might comprise the lower reflective surface of said first, second and third light guiding portion. Light that has been coupled out from the first fiber and propagated beyond the deflecting portion of that fiber is guided to the second fiber in a bound mode of the external light guide, eventually reaching the deflecting portion of the second fiber for coupling into this second fiber.

The portions of the external light guide at which the interaction between the mode in the external light guide and the light in the fiber takes place should typically be resonant, such that coupling of a particular wavelength or wavelength channel is enhanced. For any intermediate section of the external light guide, such as the portion 41 as shown in the drawings, it suffices that the mode of the external light guide is a bound mode.

The outcoupling of light might to a large degree be polarization dependent. Therefore, two optical couplers may be used, in order to couple out two orthogonal polarization directions of a wavelength channel from the core of a first fiber 20, as shown in figure 5. Both polarization directions can be coupled to the second fiber 40 by the use of two optical couplers 542 and 552, each comprising a first light guiding portion 31; 61, a second light guiding portion 44; 71 and a third light guiding portion 51; 81. These may all be designed in accordance with what has been described in relation to Figure 3 or 4. The first fiber 20 is provided with a first deflecting portion 24 (not shown in detail) for handling a first polarization direction of light propagating in this fiber, and a second deflecting portion 64 (not shown in detail) for handling a second, orthogonal polarization direction of the light propagating in this fiber. Similarly, the second fiber 40 is provided with first and second deflecting portions 54 and 84 (not shown in detail), handling two orthogonal polarization directions of light. Typically, the two deflecting portions of each fiber will be rotated 90 degrees with respect to each other about the fiber axis. For practical reasons, the fibers 20 and 40 may be arranged such that the second optical fiber 40 first runs in parallel with the first fiber 20 in a first plane. Thereafter, the second fiber 40 is rearranged such that it runs in parallel with the first fiber 20 in a second plane, which is orthogonal to said first plane. Consequently, both the first and the second optical coupler is arranged e.g. as described in relation to Figure 3 or 4, but in a mutually orthogonal relation to each other in a manner such that two orthogonal polarization directions can be handled. Hence, a first polarization direction of the propagating light is coupled out at said first deflection portion 24 of said first fiber 20, and a second polarization direction is coupled out of said first fiber 20 at the second deflection portion 64. Said first polarization direction of the light is coupled into the second fiber 40 at its first deflection portion 54, and said second polarization direction is coupled into said second fiber 40 at its second deflection portion 84.

It will be appreciated that any propagation direction described herein has been arbitrarily chosen for illustrative purposes only, and that functional symmetry can be applied for the working principle of the inventive optical coupler. Hence, by considerations about the time reversibility of electromagnetic propagation, it will be appreciated that coupling of light into an optical fiber and coupling of light out from an optical fiber may be effected in similar manners.

Conclusion

To conclude, the general idea underlying the invention is to deflect light of a selected wavelength transversally out from an optical fiber and to lead such light away from the region where it can interact with the fiber core. The light of the selected wavelength then becomes separated from the light remaining in the fiber, such that it may be handled and manipulated more conveniently. In particular, light of the selected wavelength may be guided to a second optical fiber and introduced into this second fiber transversally, also by means of a light deflector in the core of this fiber. To obtain good discrimination for the selected wavelength, the light deflected out from the optical fiber is transported by a resonant light guide in which the channel to be coupled is transported in a bound mode.

The present invention is a further development and improvement of the art disclosed in US 6 501 879, wherein the perhaps most important improvement resides in that light coupled out from the optical fiber can be more freely handled and manipulated. The light guide for transporting the light deflected from the fiber advantageously comprises a pair of reflecting surfaces, such as mirrors, wherein the separation between these mirrors is adjustable such that the spectral selectiveness of the light guide may be tuned. Therefore, the present invention preserves the advantages provided by US 6 501 879, and provides some additional important advantages.

For example, the present invention provides a broader tuneability than the prior art, since more freedom is allowed in terms of placement and design of the external light guide. In particular, when coupling light from one fiber to another, it is no longer necessary to squeeze both fibers into a narrow space between two mirrors. In the prior art, this was an obstacle, because the separation between the mirrors should be about 20 μm or less in order to provide the required tuneability.

CLAIMS

1. A spectrally selective optical coupler, comprising

a first optical fiber having a light guiding core arranged to guide light along a predetermined path, and a cladding surrounding said core;

a deflector provided in said fiber, operative to transversally deflect at least part of any light propagating in the fiber out from the fiber through the cladding;

an external light guide defined by at least a first and a second reflecting surface, wherein the optical fiber is positioned between said first and second reflecting surfaces;

the deflector being arranged in relation to the external light guide so as to deflect light from said fiber into a bound, propagating mode of the external light guide.

2. A spectrally selective optical coupler according to claim 1, wherein light from the fiber is coupled into the light guide at a deflecting portion of said fiber, and wherein said external light guide is arranged to guide said light to a region remote from said deflecting portion.

3. A spectrally selective optical coupler according to claim 2, wherein said external light guide comprises

a first light guiding portion, which is arranged to guide said propagating mode in a first direction along and beyond a first portion of said optical fiber containing said deflector;

a second light guiding portion, which is arranged to receive the propagating mode from said first light guiding portion, and to guide the propagating mode to a region remote from said optical fiber.

4. A spectrally selective optical coupler according to claim 3, further comprising

a third light guiding portion, which is arranged to receive the propagating mode from said second light guiding portion and to guide said propagating mode along a first portion of a second optical fiber, said first portion of the second optical fiber comprising a deflector operative to couple light from the propagating mode of the third light guiding portion into the second fiber.

5. A spectrally selective optical coupler according to any one of the preceding claims, wherein the separation between said first reflecting surface and said second reflecting surface of the external light guide is adjustable, such that the allowed wavelength range of the propagating mode can be tuned.

6. A spectrally selective optical coupler according to claim 5, wherein said first reflective surface is functionally divided into a plurality of sub-mirrors, the position and/or orientation of each sub-mirror being individually controllable.

7. A spectrally selective optical coupler according to any one of the preceding claims, wherein at least one of said reflective surfaces can be tilted, in order to temporarily prevent any light deflected from the fiber from entering a bound, propagating mode of the external light guide.

8. A spectrally selective optical coupler according to any one of the preceding claims, wherein said deflector is a Bragg grating.

9. A spectrally selective optical coupler according to claim 9, wherein the deflector is a blazed Bragg grating.

10. A spectrally selective optical coupler according to claim 9, wherein the blazed Bragg grating is apodized.

11. A spectrally selective optical coupler according to any one of the preceding claims, wherein at least a portion of the reflecting surface of said external light guide is a concave cylindrical surface, in order to facilitate the guiding of said propagating mode in said external light guide.

12. A method of coupling light out from an optical fiber, comprising the steps of

transversally coupling out light propagating in said fiber into a bound, propagating mode of an external light guide by deflecting at least a portion of the light at a deflecting portion of said fiber; and

guiding the outcoupled light away from said deflecting portion as a bound, propagating mode in the external light guide.

13. A method according to claim 12, further comprising the steps of

reflecting the outcoupled light back towards the deflecting portion of the fiber; and

coupling the reflected light into said fiber such that it propagates in a direction opposite the original direction.

14. A method according to claim 12, further comprising the step of

coupling said outcoupled light into another optical fiber.

15. A method according to any one of the claims 12-14, further comprising the step of

changing the separation distance between two reflective surfaces of said light guide, in order to change the coupling wavelength.

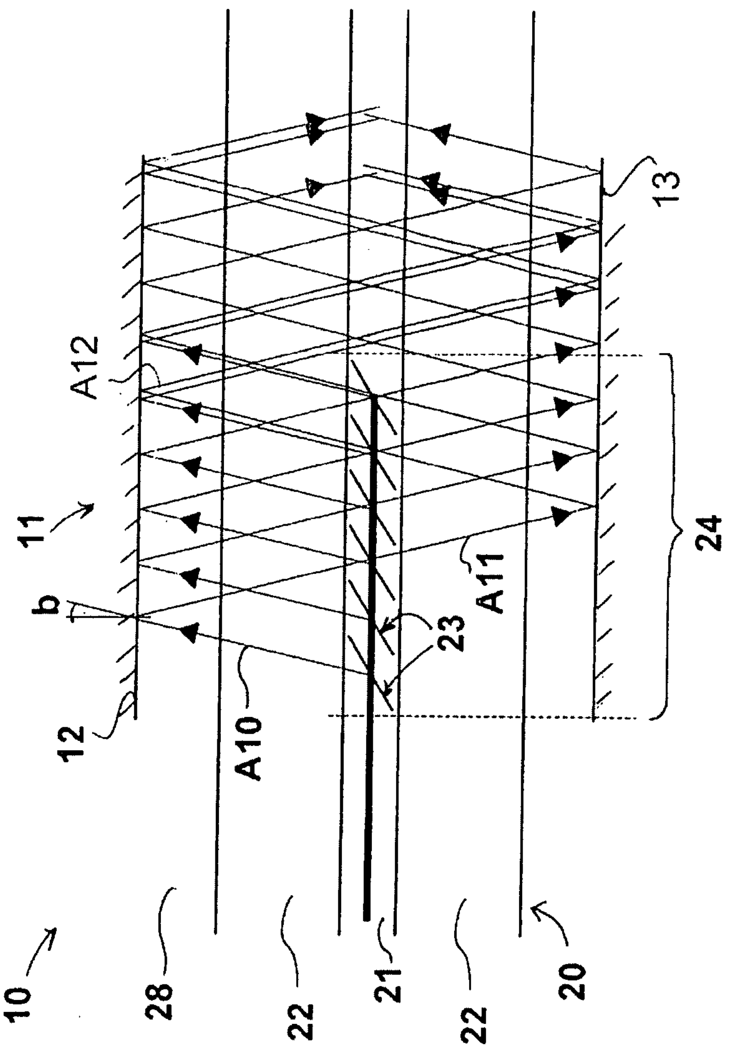


Fig. 1

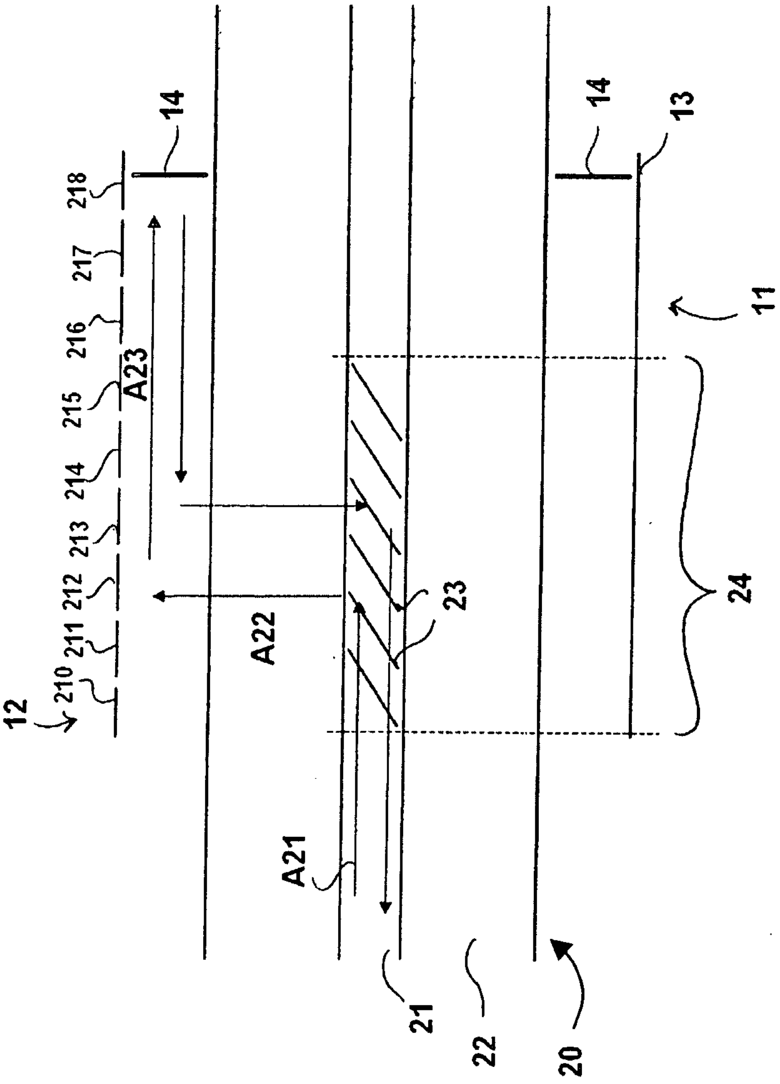

12
210
211
212
213
214
215
216
217
218
14
A23
A22
A21
23
21
22
20
24
11
14
13

Fig. 2

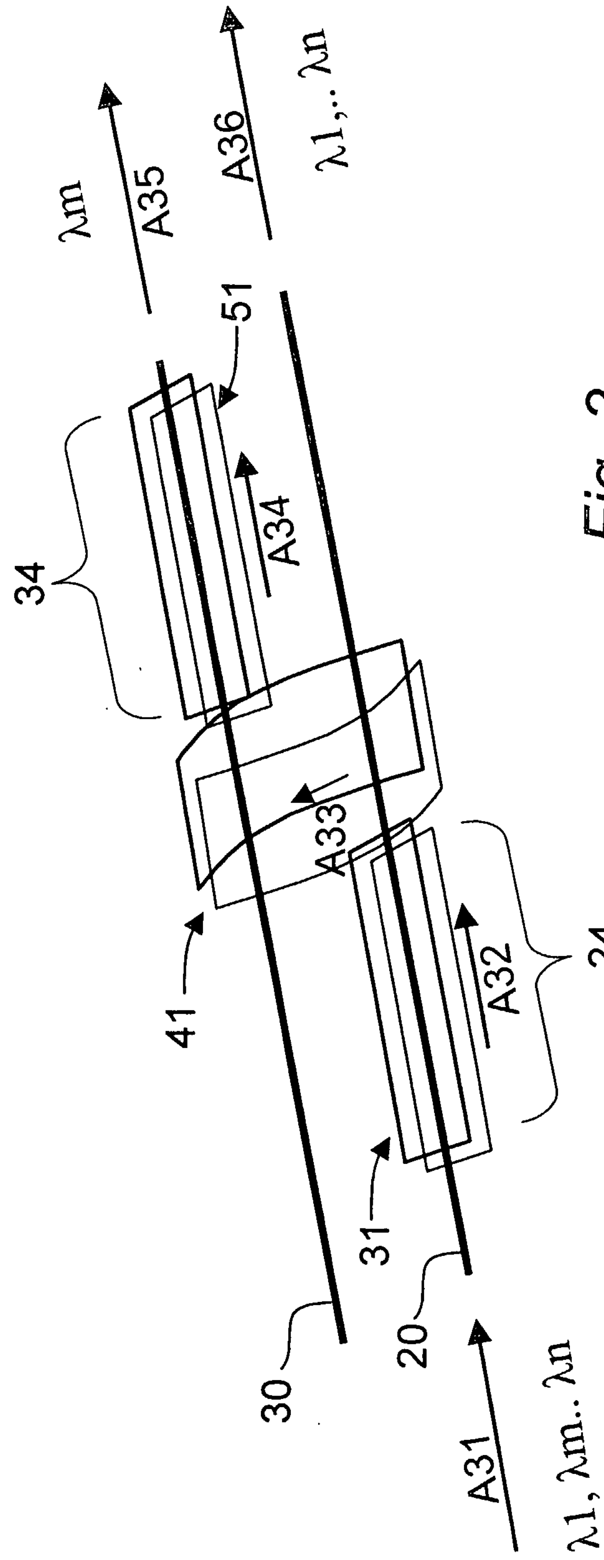


Fig. 3

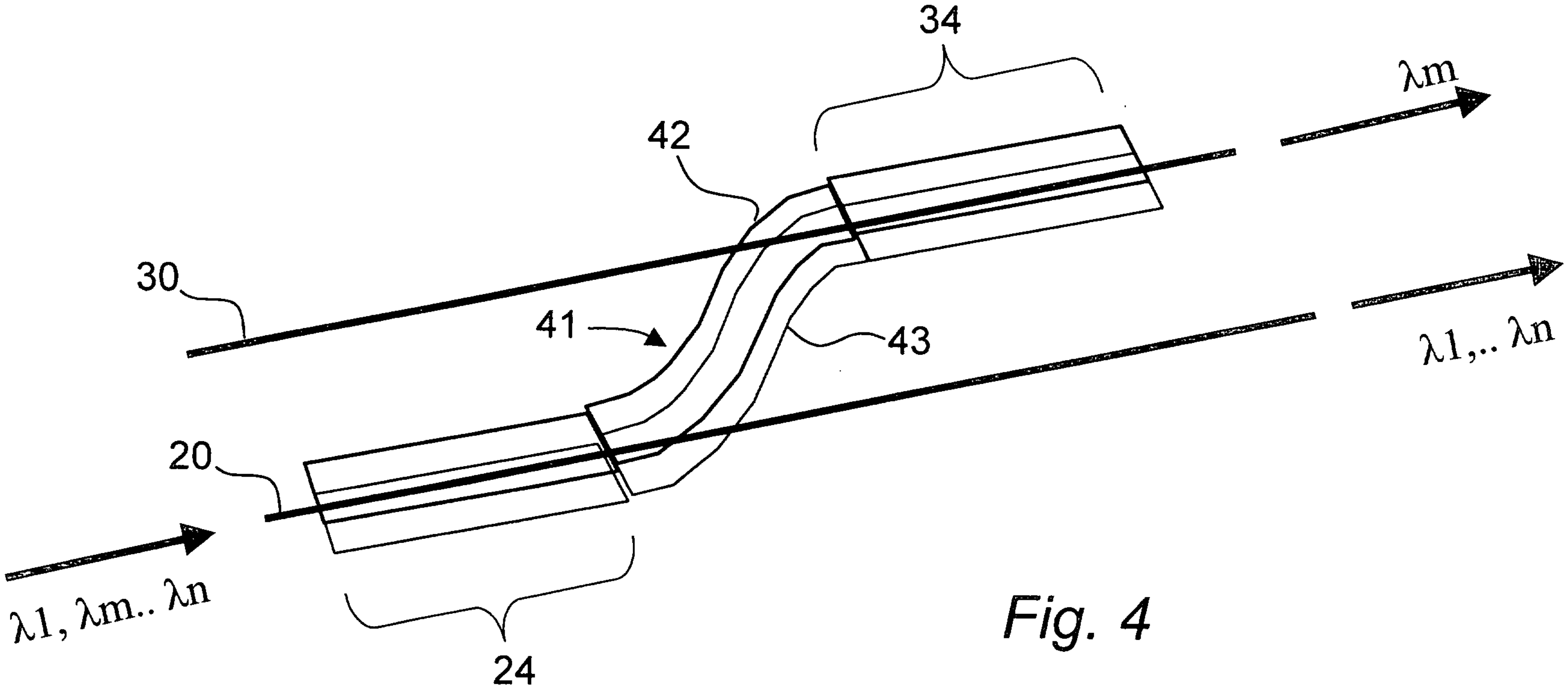

34
λm
42
30
41
43
$\lambda 1, .. \lambda n$
20
$\lambda 1, \lambda m .. \lambda n$
24

Fig. 4

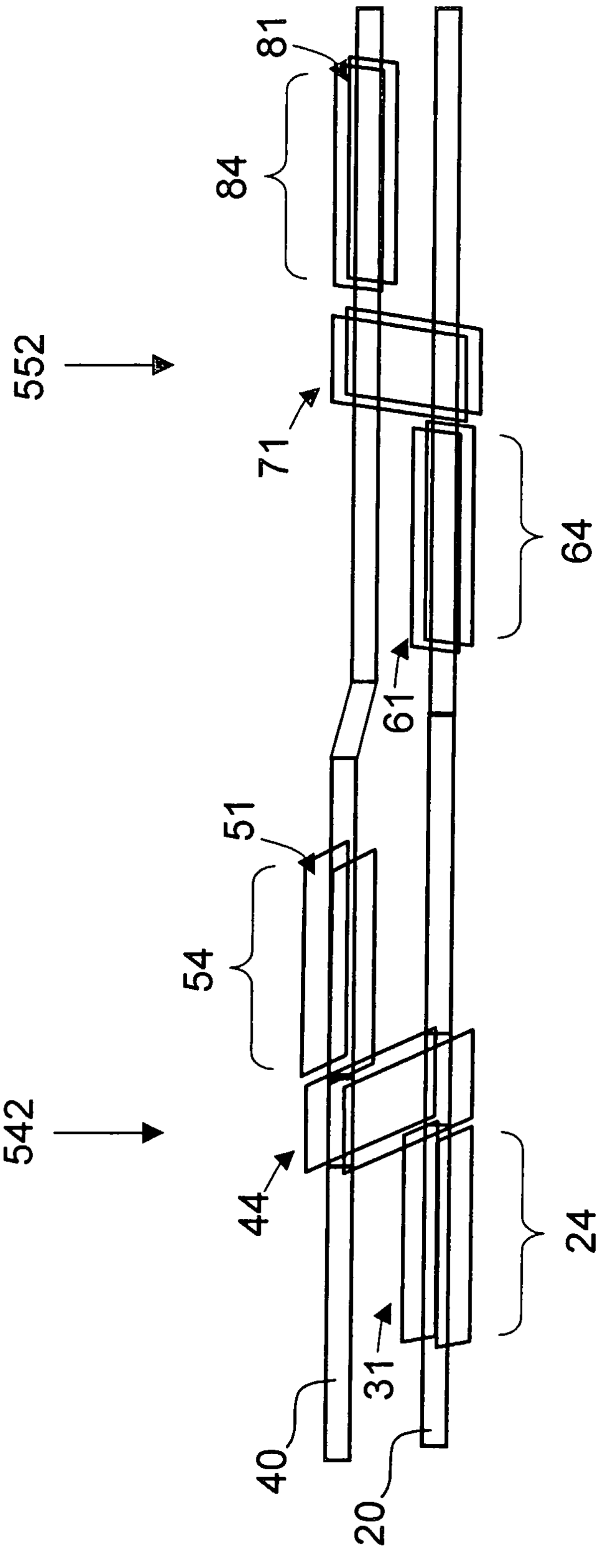


Fig. 5