

- 1 -

CORE-SELECTIVE OPTICAL SWITCHES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of provisional U.S. Patent Application Serial No. 61/428,154 to Doerr, *et al.*, filed on December 29, 2010, incorporated herein by reference. This application is related to U.S. Patent Application Serial No. 13/012,730 titled "Optical Amplifier for Multi-Core Optical Fiber" by Doerr, *et al.* filed concurrently herewith and incorporated herein by reference in its entirety.

TECHNICAL FIELD

This application is directed, in general, to optical devices and methods of using optical devices.

BACKGROUND

Optical multi-core fibers include several core regions, wherein each core region is capable of propagating substantially independent optical signals. Such fibers may provide significantly greater data capacity than a single core fiber. Thus, multi-core fibers enable significant increases to the rate of data transfer in optical systems for lower cost than would be the case for one or multiple single mode fibers.

SUMMARY

One aspect provides an optical device. The optical device includes a substrate and first and second arrays of optical couplers located along a planar surface thereof. The optical couplers of the first array are laterally arranged along the surface to end-couple in a one-to-one manner to corresponding optical cores of a

- 2 -

first multi-core fiber whose end is facing and adjacent to the first array. The optical couplers of the second array of optical couplers are laterally arranged along the surface to end-couple in a one-to-one manner to corresponding optical fiber cores of one or more optical fiber ends facing and adjacent to the second array. An optical switch network is optically connected to selectively couple some of the optical couplers of the first array to the optical couplers of the second array in a one-to-one manner.

Another aspect provides a method. The method includes forming on a planar substrate surface first and second arrays of optical couplers. The optical couplers of the first array are laterally arranged along the surface to end-couple in a one-to-one manner to corresponding optical cores of a first multi-core fiber whose end is facing and adjacent to the first array. The optical couplers of the second array of optical couplers are laterally arranged along the surface to end-couple in a one-to-one manner to corresponding optical fiber cores of one or more optical fiber ends facing and adjacent to the second array. The method includes optically connecting an optical switch network to selectively couple some of the optical couplers of the first array to the optical couplers of the second array in a one-to-one manner.

BRIEF DESCRIPTION

Reference is made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIG. 1 illustrates an embodiment of an optical switch, e.g. an example NxN core-selective switch;

- 3 -

FIG. 2 illustrates a portion of an integrated monolithic planar array of optical couplers that may be used in the optical switch of FIG. 1;

FIG. 3 illustrates optical coupling between a multicore fiber (MCF) and an integrated planar optical coupler;

FIGS. 4A and 4B illustrate location and orientation features of the coupling of a single core of an MCF to a 1-D planar grating coupler;

FIG. 5 illustrates an embodiment of an optical switch configured to independently switch different polarization modes of received optical signals;

FIG. 6 illustrates an embodiment of an optical switch configured to switch optical signals between two input MCFs and two output MCFs;

FIG. 7 illustrates an embodiment of a polarization diverse core-selective switch in which some grating couplers are configured to couple to corresponding single-core fibers (SCFs);

FIGS. 8A-8C illustrate aspects of an embodiment in which an optical switch, e.g. a Mach-Zehnder switch, is located at intersections of waveguides;

FIGS. 9A and 9B illustrate embodiments of Mach-Zehnder switches that may be used in the core-selective switch of FIG. 5A;

FIGS. 10A and 10B respectively illustrate embodiments of a Benes network and a Clos network, respectively, that may be used in the core-selective switch of FIG. 8A;

FIG. 11 illustrates an embodiment in which a core-selective switch, e.g. an NxN switch array, may be used to switch channels of WDM signals between MCFs;

- 4 -

FIG. 12 illustrates a method of forming a core-selective optical switch such as the device of FIG. 1; and

FIG. 13 illustrates an embodiment of coupling optical signals controlled by a switch network to SMFs via edge facet couplers.

DETAILED DESCRIPTION

Some optical multi-core fibers (MCFs) provide an integrated optical transport medium in which each optical core can transport an optical signal stream, simultaneously with the other optical core(s), without causing significant optical crosstalk with optical signal streams carried by the other optical core(s). For these reasons, there is a potential to replace several single-core fibers (SCFs) with a single MCF. Thus, such use of MCFs may reduce the cost and space associated with transport media for optical signals within an optical communications system. However, it is sometimes necessary to access an optical signal stream carried by a single optical core of an MCF, such as for optical processing or routing of the optical signal stream.

One device for separately accessing an individual optical core of an MCF fuses a fan-out of the optical cores of the MCF to an optical waveguide fan-out section. In such a device, single cores from the fan-out of the MCF end-connect to single optical waveguides of the optical waveguide fan-out section. Thus, the optical signals carried by the individual optical cores of the MCF are transferred to corresponding individual single-core optical fibers or optical waveguides, e.g., single-mode fibers. Once routed to individual single-core optical fibers or optical waveguides, the optical signals

- 5 -

from the different optical cores may be separately processed by optical components designed to interface to the single-core optical fibers or optical waveguides. Nevertheless, these devices can be expensive to fabricate, physically cumbersome, and not easily mass-produced. The limitations of devices based on such fan-out sections may present an impediment to the large-scale adoption of MCFs in telecommunications architectures.

Some embodiments described herein provide the functionalities of devices based on fan-out sections of MCFs without an actual fan-out section therein. In particular, the embodiments include an integrated photonic device (IPD) having one or more integrated planar arrays of optical couplers that can couple to individual optical cores of MCF(s).

Such IPDs may be formed on a surface of many micro-electronics and integrated optical substrates, e.g., a portion of a semiconductor wafer. In such IPDs, optical components may be formed on the planar surface using conventional material deposition and patterning processes. Such components may include, but are not limited to, optical gratings, waveguides, couplers, switches, lasers and photodiodes. The components of the integrated planar array are integral to each other, e.g. cannot be separated nondestructively and reassembled. An array of optical couplers is considered to be "planar" when formed on an approximately planar surface of an optical device. Such arrays may be formed, e.g. at about a same height over a substantially planar substrate such as a semiconductor wafer. A substantially planar substrate may be a planar surface or a surface having a roughly planar orientation and a surface relief patterned

- 6 -

thereon, e.g., a relief produced by micro-electronics deposition, growth, and/or etching techniques.

In various embodiments of IPDs herein, the arrays of optical couplers may be arranged to directly end-couple to the optical cores of an MCF. The optical signals carried by the separate optical cores of the MCF may be separately processed on the IPD and/or may be separately coupled to single-core optical waveguides, other MCFs or a combination thereof. The IPDs may be produced, e.g., using conventional processing methods for micro-electronics devices and integrated optical devices.

In various embodiments herein such coupler arrays are integrated with optical components on an IPD substrate to provide optical signal processing functions such as switching from one optical path to another. Some such embodiments provide inexpensive ways of integrating MCFs into optical communications architectures and/or of realizing the potential of MCFs to increase the signal-carrying capacity of optical signal transmission paths.

FIG. 1 illustrates a 1x1 optical device 100, e.g. a core-selective switch for coupling seven optical cores of one MCF to seven optical cores of another MCF. The device 100 includes a first integrated planar array 110 of optical couplers and a second integrated planar array 120 of optical couplers. Each of the integrated planar arrays 110, 120 includes a plurality of optical couplers 230, described below. As used herein, "array" excludes the trivial case of only a single optical coupler 230. Each optical coupler 230 of each of the integrated planar arrays 110, 120 is configured to optically couple to a corresponding optical core of an MCF (not shown). In various embodiments the integrated planar arrays 110, 120

- 7 -

may operate to either receive data from an MCF or to provide data to an MCF.

Each of the waveguides 130 optically couples a corresponding one of the optical couplers 230 of the integrated planar array 110 to a port of a switch network 140. Similarly, each of the waveguides 150 optically couples a corresponding one of the optical couplers 230 of the integrated planar array 120 to a port of the switch network 140. As discussed further below, the switch network 140 may provide selective switching of any one of the optical couplers 230 of the integrated planar array 110 to any one of the optical couplers 230 of the integrated planar array 120. When the integrated planar arrays 110, 120 are each optically coupled to a corresponding MCF, the switch network 140 may provide core-selective switching from any core of one MCF to any core of the other MCF.

In the illustrated embodiment, the switch network 140 may switch any of seven optical cores that couple to the seven output optical couplers 230 of the integrated planar arrays 110, 120. However, the various embodiments are not limited to any particular number of optical cores in the MCFs therein.

Optionally a wavelength add/drop multiplexer 160 may be configured to add or remove one or more channels on an optical signal propagating within one or more of the waveguides 130. The wavelength add/drop multiplexer 160 may include, e.g., a controllable phase adjuster 170, e.g. a heater, to control the add/drop function. The wavelength add/drop multiplexer 160 may be used, e.g. when the signal within the adjacent waveguide 130 propagates a wavelength-division multiplexed (WDM)

- 8 -

signal, e.g., the added and/or dropped channel(s) may be selected wavelength channel(s).

FIG. 2 illustrates a single coupler array, e.g. the integrated planar array 110 or the integrated planar array 120. The illustrated single coupler array includes segments of the seven optical waveguides 130. In the coupler array, each optical waveguide segment may include an optical coupling segment 210 and a transition segment 220. Each optical coupling segment 210 has an optical coupler 230 located thereon or therein. The optical coupler 230 is laterally positioned to optically end-couple a single corresponding optical core of an MCF (not shown). The optical coupling segments 210 may be customized to enhance their couplings to the optical cores of an MCF via the corresponding optical couplers 230, e.g., each optical coupling segment 210 may be wider than the remainder of the corresponding optical waveguide. Each transition segment 220 provides a coupler between the optical coupling segment 210 and the communication segment (shown to the right in Fig. 2) of the same waveguide. The transition segment 220 may be configured to reduce coupling/insertion losses between the differently sized coupling and communication segments of the same optical waveguide.

Examples of some grating couplers that may be suitable for use as the optical couplers 230 may be described, e.g., in U.S. Patent Application Serial No. 12/972,667 (the '667 Application) to Christopher Doerr, incorporated herein by reference in its entirety.

The optical couplers 230 are often arranged in a lateral pattern that corresponds in form and size to a lateral pattern of optical cores within an MCF whose end would approximately face and be adjacent to the optical

- 9 -

coupler, e.g., as discussed in the '667 Application. In the illustrated embodiment, the example coupler array of Figure 2 is configured to couple to seven optical cores arranged at corners and the center of a regular hexagon. However, embodiments are not limited to such an arrangement of optical cores in the MCF or to a particular number of cores in the MCF.

FIG. 3 illustrates a perspective view of a coupler array, e.g. the integrated planar array 110, located along a planar surface of a substrate 310. An MCF 320 has an end located over the coupler array and is rotationally aligned so that the individual optical cores of the MCF 320 face and optically couple to corresponding individual ones of the optical couplers of the integrated planar array 110. For example, each optical core 330 may be positioned and oriented to be able to project a light spot 360 onto a single one of the optical couplers of the integrated planar array 110 without projecting light onto other optical couplers thereof. Additional details of coupling between the MCF 320 and the integrated planar array 110 are provided in the '667 Application.

FIGS. 4A and 4B illustrate orientational and locational aspects of the coupling of the optical signal 340 to one of the optical couplers 230, e.g. a 1-D array of gratings. The projected light spot 360 produces an approximate Gaussian distribution 410 located over the corresponding optical coupler 230 with sufficient overlap to couple light from the optical signal 340 to the optical coupling segment 210.

In the illustrated embodiment the optical core 330 of the MCF makes an angle with respect the surface normal of the optical coupling segment 210 to produce a polarization-separating optical coupler. At a particular

- 10 -

angle ϕ determined in part by the wavelength of the optical signal 340, a TE polarization mode 420 of the optical signal 340 may couple to the optical coupling segment 210 with a propagation direction to the right as FIG. 4B is oriented. Similarly, a TM polarization mode 430 of the optical signal 340 may couple to the optical coupling segment 210 with a propagation direction to the left as FIG. 4B is oriented. Such coupling of TE and TM polarization modes may be used to form polarization-diverse embodiments of core-selective switches, as described further below. Additional information regarding such polarization splitting may be found in Yongbo Tang, *et al.*, "Proposal for a Grating Waveguide Serving as Both a Polarization Splitter and an Efficient Coupler for Silicon-on-Insulator Nanophotonic Circuits", IEEE Photonics Technology Letters, Vol. 21, No.4, pp 242-44, February 15, 2009, incorporated herein by reference in its entirety.

FIG. 13 illustrates a portion of an embodiment in which conventional edge facet couplers 1310 conventionally couple one or more of the optical waveguides connected to the switch network 140. Planar waveguides 1320 are representative of any of the waveguides 130, 150 of Fig. 1. The waveguides 1320 terminate at edge facets 1330 located at or near an edge of a substrate 1340. Single core fibers 1350 are located such that fiber cores 1360 optically end-couple to the edge facets 1330 such that optical signals may propagate therebetween. An edge facet coupler may be used to end-couple an optical fiber to the switch network 140 of Figure 1. Additional embodiments of edge facet couplers that may be used with embodiments of this disclosure may

- 11 -

be found in U.S. Patent Application Serial No. 13/012,693 titled "Multi-Core Optical Cable to Photonic Circuit Coupler" by Doerr, et al., filed concurrently herewith and incorporated herein by reference in its entirety.

FIG. 5 illustrates another 1x1 optical device 500, i.e., a core-selective switch for coupling one MCF to another MCF. In addition to those components described in FIG. 1, the device 500 includes a switch network 510 and optical waveguides 520, 530. The optical waveguides 520 couple optical couplers 230 of the integrated planar array 110 to the switch network 510, and the optical waveguides 530 couple optical couplers 230 of the integrated planar array 120 to the switch network 140.

The operation of the optical device 500 is described with respect to an example configuration in which the integrated planar array 110 receives optical signals from an input MCF, and the integrated planar array 120 provides received optical signals to an output MCF. As described above, the optical couplers 230 of the integrated planar array 110 couple TE and TM polarized light from the received signals in opposite directions. Thus, TE components of optical signals received from an MCF by the integrated planar array 110 propagate to the right via the waveguides 130, and TM components thereof propagate to the left via the optical waveguides 520. The switch network 140 receives the TE components, while the switch network 510 receives the TM components. The switch networks 140, 510 separately switch, e.g., the TE and TM components of received optical signals from the optical couplers 230 of the integrated planar array 110 and the optical couplers 230 of the integrated planar array 120, e.g., in any routing combinations.

- 12 -

In some embodiments of the optical device 500 of Figure 5, routing via the two switch networks 140 and 510 may be coordinated such that associated TE and TM components of light received via a particular input optical coupler 230 are routed to a same output optical coupler 230. In such cases the optical device 500 operates, e.g. as a polarization-diverse core-selective switch, because the routed optical intensity is substantially independent of the polarization of the received light.

In other embodiments, the TE and TM components of light received from the same input optical coupler 230 may be routed differently by the two switch networks 140 and 510, i.e., routed to different output optical couplers 230. In such embodiments, the optical device 500 functions as a polarization-dependent switch, which may be used, e.g., in dual-polarization optical transmitters, routers, and/or receivers.

FIG. 6 illustrates an embodiment of a 2x2 optical device 600, i.e., a core-selective optical switch. The optical device 600 has first and second integrated planar arrays 110-1, 110-2 that may operate, e.g., to receive optical signals from first and second input MCFs and has first and second integrated planar arrays 120-1, 120-2 that may operate to transmit the received optical signals to first and second output MCFs in an optical core-selective manner.

The first and second integrated planar arrays 110-1, 110-2 are configured to end-couple to the ends of the first and second input MCFs (not shown). The first and second integrated planar arrays 120-1, 120-2 are configured to end-couple to the ends of the first and second output MCFs (not shown). Optical waveguides 610

- 13 -

connect the optical couplers 230 of the first and second integrated planar arrays 110-1, 110-2 to a switch network 620. Optical waveguides 630 connect the optical couplers 230 of the first and second integrated planar arrays 120-1, 120-2 to the switch network 620. Similarly, optical waveguides 640 connect the optical couplers 230 of the first and second integrated planar arrays 110-1, 110-2 to a switch network 660, and optical waveguides 650 connect the optical couplers 230 of the first and second integrated planar arrays 120-1, 120-2 to the switch network 660.

The switch network 620 may be able, *e.g.*, to route the TE component light signals received by any one of the optical couplers 230 of the first and second integrated planar arrays 110-1, 110-2 to any one of the optical couplers 230 of the first and second integrated planar arrays 120-1, 120-2. Similarly, the switch network 660 may be able, *e.g.*, to route the TM component light signals received by any one of the optical couplers 230 of the first and second integrated planar arrays 110-1, 110-2 to any one of the optical couplers 230 of the first and second integrated planar arrays 120-1, 120-2. Thus, the optical device 600 may switch an optical signal received via an optical core of an input MCF to any optical core of a plurality of output MCFs. In some embodiments, the switch networks 620 and 660 perform correlated routing so that the 2x2 optical device 600 is polarization diverse. In other embodiments, the switch networks 620 and 660 perform separate routing of received TM and TE light so that the 2x2 optical device 600 is optical core selective and polarization selective.

FIG. 7 illustrates an embodiment of an optical device 700 for coupling two MCFs to an MCF and another

- 14 -

MCF or a set of single-core fibers (SCFs). The basis of operation of the optical device 700 is as described, e.g. for the optical device 600. In the illustrated embodiment, however, the integrated planar array 110-1 is replaced with an SCF coupler 710 for each optical coupler 230 in the integrated planar array 110-1. In some embodiments of the optical device 700, the SCF couplers 710 are placed with sufficient distance from each other that the end of a SCF may be located over each of the SCF couplers 710 simultaneously. In such embodiments, the optical device 700 may switch an optical signal between any one of the SCF couplers 710 and any one of the optical couplers 230 of the integrated planar arrays 120-1, 120-2. Thus, the optical device 700 may provide fan-in of multiple SCFs to one or more MCFs by a single, compact IPD.

FIGS. 8A-8C illustrate aspects of one embodiment of a switch network 800 that may be used, e.g. as the switch networks 140, 510, 620, and 660 of Figures 1 and 5-7. The switch network 800 includes N input/output ports 801 and N output/input ports 802, where e.g. $N=7$. An $N \times N$ array of 2×2 switches 810 (FIG. 8B) couples the input/output ports 801 and the output/input ports 802, e.g., in a one-to-one manner. In the illustrated embodiment, the input/output ports 801 may receive or provide optical signals from/to the waveguides 150, and the output/input ports 802 may provide or receive optical signals to/from the waveguides 130. The array of switches 810 may provide $N \times N$ switching of signals propagated by the waveguides 130 and the signals propagated by the waveguides 150. Herein, an $N \times N$ array of switches 810 may connect the input/output ports 801 to the output/input ports 802 in a one-to-one manner.

- 15 -

Each embodiment of the 2x2 switch 810 is located at an intersection of a vertical waveguide 820 (FIG. 8B) and a horizontal waveguide 830. In one embodiment the 2x2 switch 810 is a 2x2 Mach-Zehnder interferometer (MZI). FIG. 9A illustrates an embodiment in which the 2x2 switch 810 comprises an MZI switch 905. In the 2x2 MZI, a 2x2 input optical coupler 910 couples two input waveguides 915, 920 to two internal optical waveguides. In the 2x2 MZI, a 2x2 output coupler 925 couples the two internal optical waveguides to two output waveguides 930, 935. In the (MZI) 940, one of the two internal optical waveguides has an optical path length that is controllable, e.g. by an optical phase shifter electrically controlled via a control 945. As appreciated by those skilled in the optical arts, suitably controlling the relative phase of the optical paths of the MZI 940 can switch light received by one of the input waveguides 915, 920 to either selected one of the output waveguides 930, 935. Multiple, e.g. N^2 , instances of the of the 2x2 MZI switch 905 may provide the individual switches for performing the routing between the N input/output ports 801 and the N output/input ports 802 of the switch network 800.

FIG. 9B illustrates an embodiment in which the switch 810 includes four MZI switches 905 cross-coupled as illustrated. Each MZI switch 905 is configured such that one input waveguide 915, 920 or one output waveguide 930, 935 is unused. Thus two instances of the MZI switch 905 have only one input, and two instances of the MZI switch 905 have only one output. The embodiment of FIG. 9B may, e.g. provide better isolation between the optical signals received by the switch 810.

Returning to FIG. 8C, illustrated is an embodiment in which more than one switch 810 may be operated

- 16 -

simultaneously to effect splitting of an optical signal. For example, an optical signal received on the vertical waveguide 820 may be split between the horizontal waveguide 830 and another horizontal waveguide 850 by simultaneously partially operating the switch 810 and a switch 840. Each switch 810, 840 may include, e.g. a 2x2 MZI switch 905. The 2x2 MZI switch 905 may be operated such that a portion of the optical power received at one of the input waveguides 915, 920 is routed to each of the output waveguides 930, 935. The switch 810 may thus be operated, e.g. such that less than all the optical power received thereby from the vertical waveguide 820 is directed to the horizontal waveguide 830. The switch 840 may be operated such that all the remaining optical signal power is directed to the horizontal waveguide 850. In some embodiments the switch 840 directs only a portion of the power received thereby to the horizontal waveguide 850, with the remaining portion directed to another switch.

In some embodiments, the switch networks 140, 510, 620, and 660 may have other constructions than networks of interconnected MZIs. For example, the switch networks 140, 510, 620, and 660 may include a Benes network 1010 as illustrated in FIG. 10A or a Clos network 1020 as illustrated in FIG. 10B or a fan-out-and-select network (not shown) may be used. Further information on Benes and Clos networks may be respectively found in, e.g. Guido Maier, *et al.*, "Optical-Switch Benes Architecture based on 2-D MEMS", 2006 Workshop on High Performance Switching and Routing (IEEE), pp.6, doi: 10.1109/HPSR.2006.1709718, and U.S. Patent No. 6,696,917 to Heitner, *et al.* Each of the networks 1010, 1020 is an NxN network, and includes N inputs and N outputs, where N equals, e.g. seven. In

- 17 -

another embodiment the switch networks 140, 510, 620, and 660 include a fanout-and-select architecture. In this architecture, a tree arrangement of 1x2 switches branches N input ports to N^2 waveguides and then a tree arrangement of 2x1 switches connects the N^2 waveguides to N output ports. In some embodiments switches may include the use of micro-electrical-mechanical (MEM) devices such as individually actuated micromirrors to provide for reconfigurable optical routing via free space devices rather than integrated optical devices.

FIG. 11 schematically illustrates an embodiment of an IPD 1100 in which a switch network 1105 may be used to effect wavelength-selective switching of individual channels of a WDM signal between optical couplers 1125, 1130, 1170, 1175. First and second fiber cores 1107, 1110 provide N, e.g. first and second input WDM signals 1115, 1120. In various embodiments, the fiber cores 1107, 1110 may be optical cores from a single MCF or different optical fibers. In some embodiments at least one of the fiber cores 1107, 1110 is a core from an SCF.

The first input WDM signal 1115 includes m channels, e.g. with wavelengths λ_{11} , λ_{12} , λ_{13} , λ_{14} . The second input WDM signal 1120 also includes m channels, e.g. with wavelengths λ_{21} , λ_{22} , λ_{23} , λ_{24} . In other embodiments, the number of channels provided by the WDM signal 1115 may be different than the number of channels provided by the WDM signal 1120. Optical couplers 1125, 1130, e.g. such as those described by the optical coupler 230, couple the WDM signals 1115, 1120 to respective first and second demultiplexers 1135, 1137. The demultiplexer 1135 separates a first WDM input channel set 1140, and the demultiplexer 1137 separates a second WDM input channel

- 18 -

set 1142. In some embodiments an add/drop multiplexer 1143 may be used to remove one or more wavelength-channels from and/or add one or more wavelength-channels to, the set(s) of wavelength channels of the WDM signals 1115, 1120.

The switch network 1105 receives the input wavelength-channel sets 1140, 1142 at $m \times N$ inputs. The switch network 1105 provides output wavelength-channel sets 1147, 1155 at $m \times N$ outputs. In some embodiments the switch network 1105 may be controlled to switch any of the wavelength-channels of the first input channel set 1140 with any of the wavelength-channels of the second input channel set 1142. Thus, as in the illustrated example, the λ_{12} channel is grouped with λ_{21} , λ_{23} , λ_{24} channels in the channel group 1155, and the λ_{22} channel is grouped with λ_{11} , λ_{13} , λ_{14} channels in the channel group 1147. In various embodiments, WDM wavelength-channels at a particular wavelength, e.g. λ_{12} and λ_{22} , may be swapped among two or more output cores so that no WDM wavelength-channels are superimposed onto a same output core, as in the illustrated embodiment.

A first multiplexer 1145 combines the first output wavelength-channel set 1147 to produce a first output WDM signal 1150. A second multiplexer 1160 combines the second output wavelength-channel set 1155 to produce a second output WDM signal 1165. The first and second output optical couplers 1170, 1175 respectively couple the output WDM signals 1150, 1165 to first and second output fiber cores 1180, 1185. In various embodiments the fiber cores 1180, 1185 may be optical cores from a same MCF or optical cores of different optical fibers. In some

- 19 -

embodiments at least one of the fiber cores 1180, 1185 is a core from an SCF.

FIG. 12 illustrates a method 1200 for forming an optical device, e.g., the optical devices 100, 500, 600, and 700 of Figures 1, 5, 6, and 7. The method 1200 will be described without limitation by making exemplary references to the various embodiments described herein, e.g. by FIGs. 1-11. The steps of the method 1200 may be performed in an order other than the illustrated order.

A step 1210 includes forming a first integrated planar array of optical couplers, e.g. the integrated planar array 110, having a first plurality of optical couplers, e.g. instances of the optical coupler 230. The optical couplers of the first plurality are configured to couple a corresponding plurality of optical signals to a first plurality of optical cores of a first multi-core fiber, e.g. the MCF 320.

A step 1220 includes forming a second integrated planar array of optical couplers, e.g. the integrated planar array 120, having a second plurality of optical couplers, e.g. instances of the optical coupler 230. The optical couplers of the second array are configured to couple the plurality of optical signals to a second plurality of optical cores, e.g., of the MCF 320.

A step 1230 includes forming a switch network that is able to optically couple in a one-to-one manner optical couplers of the first plurality of optical couplers to optical couplers of the second plurality of optical couplers.

The following provides various optional features of the method 1200. In some cases these optional features may be combined.

- 20 -

The optical couplers of the second array may be laterally arranged along the substrate surface to end-couple in a one-to-one manner to corresponding optical cores of a second multi-core fiber whose end is facing and adjacent to the second array. The first and second pluralities of optical couplers may each include N optical couplers. The switch network may include an array of 2x2 Mach-Zehnder interferometers configured to implement NxN switching. The first and second pluralities of optical couplers may each include N optical couplers, and the switch network may comprise an NxN Clos network or an NxN Benes network.

The switch network may include a first switch network connected to switch a first polarization mode of received optical signals and a second switch network connected to switch a second polarization mode of the received optical signals.

The second plurality of optical couplers may include grating couplers configured to couple light to a corresponding plurality of single core fibers.

The couplers of the second plurality of optical couplers may include edge facet couplers.

An optical path between the first and second plurality of the optical couplers may include an add/drop multiplexer.

Each of the first plurality of optical couplers may be coupled to a corresponding optical core of a multi-core optical fiber.

The switch network may include separate first and second optical switching networks. The first optical switching network may be connected to receive light of a linear polarity from one of the optical couplers of the first array that is orthogonal to a linear polarity of

- 21 -

light that the second switching network is connected to receive from the same one of the optical couplers of the first array.

The optical couplers of the second array may be configured to couple light to a corresponding plurality of single core fibers.

The optical device may further include a multi-core optical fiber having an end facing and adjacent to the second array to end-couple optical cores of said multi-core optical fiber to corresponding ones of the optical couplers of the second array.

An optical path between said first and second plurality of couplers may include an add/drop multiplexer.

A first demultiplexer may be configured to separate optical wavelength channels from a first WDM signal. A second demultiplexer may be configured to separate optical wavelength channels from a second WDM signal. First optical ports of the switch network may connect to corresponding outputs of the first optical demultiplexer, and the second optical ports of the switch network may connect to corresponding outputs of the second optical demultiplexer.

First and second multiplexers may be configured such that the first multiplexer is configured to combine optical wavelength channels to a first WDM signal, and the second multiplexer is configured to combine optical wavelength channels to a second WDM signal. The inputs of the first optical multiplexer may be connected to a first set of optical ports of the switch network. The inputs of the second optical multiplexer may be connected to a second set of optical ports of the switch network.

- 22 -

Those skilled in the art to which this application relates will appreciate that other and further additions, deletions, substitutions and modifications may be made to the described embodiments.

- 23 -

WHAT IS CLAIMED IS:

1. An optical device, comprising:

a substrate having a planar surface;

a first array of optical couplers located along the surface, the optical couplers of the first array being laterally arranged along the surface to end-couple in a one-to-one manner to corresponding optical cores of a first multi-core fiber whose end is facing and adjacent to the first array;

a second array of optical couplers located along the surface, the optical couplers of the second array being laterally arranged along the surface to end-couple in a one-to-one manner to corresponding optical fiber cores of one or more optical fiber ends facing and adjacent to the second array; and

an optical switch network optically connected to selectively couple some of the optical couplers of the first array to the optical couplers of the second array in a one-to-one manner.

2. The optical device recited in Claim 1, wherein an optical path between said first and second plurality of couplers includes a wavelength add/drop multiplexer.

3. The optical device recited in Claim 1, wherein the optical couplers of the second array are laterally arranged along the surface to end-couple in a one-to-one manner to corresponding optical cores of a second multi-core fiber whose end is facing and adjacent to the second array.

- 24 -

4. The optical device recited in Claim 3, wherein said switch network includes separate first and second optical switching networks, said first optical switching network being connected to receive light of a linear polarity from one of the optical couplers of the first array that is orthogonal to a linear polarity of light that the second switching network is connected to receive from the same one of the optical couplers of the first array.

5. The optical device recited in Claim 3, further comprising a first multiplexer configured to combine optical wavelength channels to a first WDM signal and a second multiplexer configured to combine optical wavelength channels to a second WDM signal, wherein said switch network has first and second sets of optical ports, the first optical ports connecting to corresponding inputs of the first optical multiplexer and the second optical ports connecting to corresponding inputs of the second optical multiplexer.

6. A method, comprising:

forming a first planar array of optical couplers along a surface of a substrate, the optical couplers of the first array being located to couple in a one-to-one manner to corresponding optical cores of a first multi-core fiber whose end is facing and adjacent to the first array;

forming a second planar array of optical couplers on the planar substrate, the optical couplers of the second array being located to couple in a one-to-one manner to corresponding optical fiber cores of one or more optical fiber ends facing and adjacent to the second array; and

- 25 -

forming an optical switch network on the substrate such that optical ports of the switch array connect in a one-to-one manner to the optical couplers of the first array and optical ports of the switch array connect in a one-to-one manner to the optical couplers of the second array.

7. The method recited in Claim 6, wherein said optical couplers of said second array are configured to couple light to a corresponding plurality of single core fibers.

8. The method recited in Claim 6, wherein the optical couplers of the second array are laterally arranged along the surface to end-couple in a one-to-one manner to corresponding optical cores of a second multi-core fiber whose end is facing and adjacent to the second array.

9. The method recited in Claim 8, wherein said switch network includes separate first and second optical switching networks, said first optical switching network being connected to receive light of a linear polarity from one of the optical couplers of the first array that is orthogonal to a linear polarity of light that the second switching network is connected to receive from the same one of the optical couplers of the first array.

- 26 -

10. The method recited in Claim 8, further comprising configuring a first demultiplexer to separate optical wavelength channels from a first WDM signal and configuring a second demultiplexer to separate optical wavelength channels from a second WDM signal, wherein said switch network has first and second sets of optical ports, the first optical ports connecting to corresponding outputs of the first optical demultiplexer and the second optical ports connecting to corresponding outputs of the second optical demultiplexer .