

FREE-SPACE NON-BLOCKING SWITCH

TECHNICAL FIELD

The invention concerns an optical switch, and in particular a non-blocking free-space switch.

BACKGROUND OF THE INVENTION

5 The tantalizing prospect of utilizing optical wiring in a Silicon-based electronic environment becomes ever more attractive as speed, complexity and integration density increase. Tremendous incentives are increasingly apparent for the development of optical and optoelectronic devices that are compatible with VLSI (Very Large Scale Integrated) Silicon (Si) technology. Large-area and low-cost Si wafer technology provides an ideal platform for
10 photonic guided-wave devices. In addition, mature Si processing technology, micromachining techniques, Silicon-on-Insulator (SOI) and heteroepitaxy, can be used to fabricate complex optical structures such as micro-optical devices and hybrid optoelectronics. Compatibility with mainstream Si Integrated Circuit (IC) technology promises low cost and reliable manufacturing of monolithic Si-based optoelectronic integrated circuits that will be
15 much like today's electronic ICs.

Optical switches, very much like the conventional transistor, are essential components of photonic guided-wave devices. Optical switching is needed for rearranging the optical paths in a telecommunication network, for example.

Most optical switches have one or more elements that are mechanically actuated. These kind
20 of switches are thus referred to as optomechanical switches. Typical examples are addressed in "Current European WDM deployment trends", E. Lowe, IEEE Commun. Mag., Vol. 36, pp. 46-50, 1998, and in "All-silicon bistable micro mechanical fiber switches", M. Hoffmann et al., Electron. Lett., Vol. 34, pp. 207-208, 1998.

It is desirable to have optical switches that are less bulky and more reliable than
25 optomechanical switches. An often followed approach to build an NxM optical switch is to cascade a (large) number of simple 2x2 optical switching elements, where each of these 2x2 switches consists of one or two tunable Mach-Zehnder interferometers. An example of such a

switch is described in "Low-Loss and High-Extinction-Ratio Silica-Based Strictly Nonblocking 16x16 Thermo-optic Matrix Switch", T. Goh, M. Yasu, K. Hattori, A. Himeno, M. Okuno and Y. Ohmori, IEEE Photonics Technology Letters, Vol. 10, No. 6, June 1998. A second approach, which uses beam-steering to realize a 1xN or Nx1 switch is described in "Compact Versatile Thermo-optical Space Switch Based on Beam Steering by a Waveguide Array", E. Flück et al., IEEE Photonics Techn. Lett., Vol. 11, No. 11, pp. 1399-1401, November 1999. This integrated optical switch resembles known arrayed waveguide grating (AWG) wavelength multiplexers. It consists of a number of input waveguides, a star coupler that divides the input light over an array of channel waveguides and a second star coupler that refocuses the light from the array onto one of the output waveguides. The array waveguides at the input side are equipped with tunable lenses. By adjusting the phase distribution one can determine onto which output waveguide the light is focussed. This allows to switch input signals to desired output channels. This IEEE publication is herewith incorporated by reference.

It is an object of the present invention to provide a switch which is simple and inexpensive to fabricate and which switches light paths rapidly and without frictional wear to the switch.

It is another object of the present invention to provide a switch which can be integrated with other components (e.g., optical components) on a substrate.

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SUMMARY OF THE INVENTION

The present invention concerns optical switches and data transmission systems comprising one or more such switches. A switch, in accordance with the present invention, comprises an input channel with an input optical free space element, a large optical free space element, an input tunable optical lens with adjustable projection characteristic for projecting a light wave received from the input optical free space element into the large free space element. In addition, the switch comprises an output channel with an output

optical free space element, and an output tunable optical lens with adjustable receiving characteristic for capturing the light wave from the large free space element and for feeding the light wave to the output optical free space element.

5 DESCRIPTION OF THE DRAWINGS

The invention is described in detail below with reference to the following schematic drawings. It is to be noted that the Figures are not drawn to scale.

FIG. 1A-1F is a sequence of schematic cross-sections illustrating the fabrication of a ridge waveguide structure, according to the present invention.

10 **FIG. 2A** is a schematic top view of a tunable optical lens, according to the present invention.

FIG. 2B is a schematic top view of an input optical free space element, according to the present invention.

15 **FIG. 2C** is a schematic top view of an output optical free space element, according to the present invention.

FIG. 3A-3B are schematic top views of a first switch, according to the present invention.

FIG. 4 is a schematic top view of a second switch, according to the present invention.

FIG. 5 is a schematic top view of a third switch, according to the present invention.

FIG. 6 is a schematic top view of a fourth switch, according to the present invention.

20 **FIG. 7** is a schematic top view of a fifth switch, according to the present invention.

FIG. 8 is a schematic top view of a sixth switch design, according to the present invention.

FIG. 9 is a schematic top view of a seventh switch design, according to the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS:

Before different embodiments of the present invention are described, the basic elements and building blocks as well as the underlying integrated planar waveguide technology, in accordance with the present invention, are addressed.

- 5 The present switch can be implemented in various material systems including Silicon oxinitride (SiON), III-V semiconductors like InP, silica (i.e., SiO₂) glasses, lithiumniobate, and polymers.

Optical waveguides are employed that guide light waves to the switch and away from the switch. An optical waveguide usually comprises a core made of some high-refractive index
10 material and a cladding of a low-refractive index material. The core and cladding may be made of doped silica glass, where the necessary refractive index contrast is achieved by an appropriate doping profile. For mass production it is desirable to fabricate the waveguides on a semiconductor technology compatible substrate, such as a Si wafer (e.g., a four inch Si wafer), or on a glass substrate. This results in what is called a planar waveguide or an
15 integrated planar waveguide. A review on planar waveguide technology is given in "Silica-based optical integrated circuits", by Y.P.Li, C.H.Henry, IEE Proc.-Optoelectron. Vol. 143, No. 5, pp. 263-280, October 1996.

If the cladding is made of silica, which has a refractive index of 1.45, for the core a material with a higher refractive index (e.g., near 1.5) is desired. Note that a higher index
20 gives smaller devices, but also higher loss, more difficult fiber-to-chip-coupling etc. SiON can be chosen for the core, because its refractive index can be tuned over a wide range by changing the nitrogen concentration of the material. An example for use of SiON as waveguide is described in US patent 5,416,861.

In "Plasma-enhanced growth, composition and refractive index of SiON films" by K.E.
25 Mattsson in J. Appl. Phys.77, No. 12, 15 June 1995, pp. 6616-6623, the variation of nitrogen in SiON for changing the refractive index is examined.

A particular feature of SiO_xN_y resulting from a mixture of the components SiO_2 and Si_3N_4 is that it forms amorphous structures and that the components are miscible over the whole possible range. A typical composition of the waveguide core is $\text{SiO}_{1.9}\text{N}_{0.08}$.

5 A known fabrication technique is to deposit SiON using a Plasma Enhanced Chemical Vapor Deposition (PECVD) process. The resulting material has, however, a large hydrogen concentration. Hydrogen is incorporated in the form of hydroxyl groups, Si-H groups and NH- and NH_2 -fragments. These groups and fragments introduce additional absorption into the optical transmission characteristic of the silicon oxynitride. The first overtone of the NH-induced absorption band lies at 1505 nm and overlaps with the spectral window, which is
10 used for optical signal transmission and which extends from 1540 nm to 1570 nm, hereinafter simply referred to as the optical transmission window. This window has been chosen for optical transmission due to the fact that silica glass there has its lowest absorption and that erbium-doped optical amplifiers there have the range of most linear amplification as can be read upon in "Review of rare earth doped fiber lasers and amplifiers" by P. Urquhart, IEE Proc.
15 Vol. 135, Pt. J, No. 6, pp 385-407, December 1988.

This absorption results in often unacceptably large losses for viable products. The NH concentration may even increase with time and humidity due to natural exchange with the surrounding medium. The hydrogen concentration and with it the resulting absorption losses are therefore currently reduced by a high-temperature annealing process as described in "High
20 contrast and low loss SiON optical waveguides by PECVD", by B. Offrein et al. in Proceedings 1996 Symposium of the IEEE/LEOS Benelux Chapter, Enschede, pp. 290-293, which process consolidates the material, and reduces the hydrogen concentration by evaporating water and ammonia. This document is incorporated herein by means of reference. The nitrogen atoms change their atomic neighborhood from two silicon atoms and one
25 hydrogen atom to three silicon neighbors. The losses can however be reduced only to a certain extent, because longer annealing times are assumed to produce additional scattering centers, which is ascribed to crystallization or phase separation. Another approach to reduce the hydrogen content in SiON is described in "Low-Hydrogen Silicon Oxynitride Optical Fibers Prepared by SPCVD" by Dianov et al. in Journal of lightwave technology, Vol. 13, No. 7, July
30 1995.

A well suited, special class of SiON materials is disclosed in the co-pending PCT patent application PCT/IB98/01017, with International Publication number WO 99/44937. This PCT patent application, which is currently assigned to the assignee of the present application, is incorporated by reference.

- 5 The following embodiments will be illustrated in connection with IBM's high-index-contrast silica-on-silicon integrated planar waveguide technology which allows to make low-cost silica on silicon integrated planar lightwave components for optical networks. This integrated planar waveguide technology makes use of a large effective refractive index contrast that can be achieved in waveguides formed by SiON and SiO₂.
- 10 This enables the realization of waveguides with small bending radii and thus considerable device miniaturization.

- Details of the high-index-contrast silica-on-silicon technology are addressed in "Wavelength division multiplexed add/drop ring technology in corporate backbone networks", G.L. Bona et al., Opt. Eng. Vol. 37, pp. 3218-3228, 1998. This document is
- 15 herein incorporated by reference.

- The term waveguide array, as herein used, is meant to refer to an array of channel waveguides. Ridge waveguide (also called stripe waveguide) structures, buried waveguide structures and any other structure is well suited for use in connection with the present invention. For the array waveguides a number of different shapes and geometry can be
- 20 applied. Note that in the Figures for sake of simplicity only waveguide arrays with straight waveguide channels are shown. In most practical applications these waveguide channels are bent, as shown in Figure 9, for example.

The word channel refers to one particular link of a communication link that carries a multiwavelength light wave.

- 25 An optical free space element has a free propagation region where light is not laterally confined. Light can be projected from an input waveguide (herein referred to a input channel) or input waveguide array into such an optical free space element. Optical free

space elements are in the literature also referred to as free propagation regions (FPRs). We herein make a distinction between input optical free space elements, large optical free space elements, and output optical free space elements. This is an artificial distinction which is merely introduced in order to be able to better describe the different components of a switch, their arrangement, and their function.

A “tunable lens”, as herein used, comprises a waveguide array plus phase shifters (e.g., heaters). This tunable lens takes a divergent or parallel beam propagating in a first optical free space element (e.g., an input optical free space element) and transforms this beam into a parallel or convergent beam in a second optical free space element, just like a normal lens would do. For the purposes of the present description, everything between the first optical free space element and the second optical free space element makes up the tunable lens.

The focusing properties of the waveguide array and the wavelength dependency are determined by the relative effective optical lengths of the waveguides in the waveguide array. This effective optical length is determined by the effective index of refraction and the physical length of the waveguide. It can be fine-tuned using the phase shifters (e.g., heaters).

The substitution of a normal lens, which applies a continuous phase modulation to a continuous wavefront, by a waveguide array, which applies a discrete number of phase shifts to a discrete number of sub-waves, introduces extra losses and spurious diffracted light beams. These effects, and the way to minimize them, are well known to a person skilled in the art of AWG design. In general, the more waveguides the array consists of, the better it approximates a continuous lens, and the less important these side-effects are. However, with more waveguides in an array, more phase shifters (e.g., heaters) are needed for controlling the tunable lens.

This holds for the herein described SiON technology where one needs the heaters also to correct spurious phase errors in the waveguides. However, if one uses a very well controlled technology, without these phase errors, it is possible to employ only two heaters: one to apply linear phase gradients (steering) and one to apply quadratic phase gradients (focal distance) with many array waveguides.

A tunable lens can be implemented in different manners. A typical example is a tunable lens that comprises an individually tunable heater for some or all of the waveguides of a waveguide array. Under certain circumstance it is desirable to employ more than one heater per waveguide.

- 5 By adjusting the heaters one can control the projection characteristic of the light beam emitted into a free space element. Depending on the implementation one can either adjust the focal point (focal distance) or the direction of light emission (steering), or both at the same time. A linear phase gradient leads to a tilting (steering) of the phase front of the light emitted. With quadratic or higher order phase gradients one can change the focal
10 distance of the light wave. In other words, such a tunable lens allows a thermo-optical control of the projection characteristic.

- Well suited are heaters that comprise chromium pads or lines that are placed close to the waveguide that is to be influenced. Aluminum leads can be used to drive current through the chromium pads or lines. A current or voltage source is needed for driving the
15 individual heaters. Such a current or voltage source and other elements/circuits can be part of a heater steering unit. Such a heater steering unit may comprise a microcomputer and a memory to store the respective heater settings, or it may be connected to a switch control box or a computer (e.g., via a computer interface). A switch control box obtains/extracts routing or switching information (connection information) either from the packets or
20 frames received on the input side of the switch, or this connection information is received from other systems. The respective connections are then established inside the switch/optical chip via the heater steering unit and the input- and output tunable lenses.

- In order to find the optimum heater settings corresponding to the various switch states, one can use an iterative optimization procedure. Well suited is a Levenberg-Marquard
25 algorithm, as described in "Numerical Recipes in C: The Art of Scientific Computing", Cambridge, Cambridge Univ. Press, pp. 683-688, 1988. The respective heater settings can be stored so that they can be recalled when needed to change the switch state(s). Such a reconfiguration can be done in the ms range.

Micromechanical on-chip elements can also be used to realize a tunable lens.

Before detailed implementations of the present invention are addressed, the basic components of a switch, in accordance with the present invention, and its operation are discussed.

5 The basic elements of a switch, in accordance with the present invention, are: an input optical free space element, an input tunable lens, a large optical free space element, an output tunable lens, and an output optical free space element.

10 The path for a connection through the switch is as follows: light from an input channel is launched into an input optical free space element and becomes a laterally divergent beam. This divergent beam is picked up by the first tunable lens (waveguide array plus heaters) and transformed into a parallel or convergent beam in the large optical free space element. At the end of this large optical free space element the beam is still parallel, or divergent again (past the focal point). This parallel or divergent beam is picked up by the second tunable lens (second waveguide array plus heaters) and transformed into a convergent beam in the output optical free space element. The position of the focal point in this element is adjusted such that
15 it coincides with the start of the output waveguide. The light is then coupled into this output waveguide and leaves the switch through it.

20 The NxN switching functionality is obtained by adjusting the input tunable lens to steer the direction of the beam in the large optical free space element. For a number of different settings, this beam can be pointed into the direction of a number of different output tunable lenses. In the same way, the output tunable lenses can be adjusted such that for a number of different settings, beams coming from different input tunable lenses are projected onto the waveguides of the output waveguide arrays.

An optimal link between a given input waveguide P and a given output waveguide Q is only made when:

25 a) the input tunable lens P is set to point the transmitted beam into the direction of the output tunable lens Q, and

b) the output tunable lens Q is set to focus a beam coming from the input tunable lens P onto the output waveguide Q, and

c) Either: c1) The focal length of the input tunable lens P is set to transmit a parallel beam in the large optical free space element and the output tunable lens Q is set to refocus such a parallel beam onto the output waveguide.

Or: c2) The focal length of the input tunable lens P is set to transmit a convergent beam with a focal point in the large optical free space element half-way between the input and the output tunable lenses, and the output tunable lens Q is set to refocus the divergent beam after this focal point onto the output waveguide.

10 If the directions or the focal distances of the tunable lenses slightly deviate from the above mentioned scenarios, there might still be some coupling, but with less than optimum coupling efficiency. This can be used for power adjustments.

Important optical properties of the switches according to the present invention are the transmission loss, output channel loss uniformity, channel isolation, etc. Given a fixed waveguide technology, the free design parameters that can be used to adjust properties of the switch are well known and understood by a person of skill in the art. Analytical as well as numerical modeling or simulation tools can be used when designing a switch according to the present invention. This procedure follows the same considerations as applied when modeling standard AWG devices.

20 An exemplary cross-section of a waveguide with a ridge structure is shown schematically in Figure 1F. For the fabrication different steps are needed, as illustrated in Figures 1A - 1F. A Si substrate 20 (e.g., a Si wafer) is thermally oxidized to form a SiO₂ layer 21 (also referred to as lower cladding), as shown in Figure 1A. In a subsequent step, a SiON core 22 is grown by using a PECVD process. The result of this PECVD step is illustrated in Figure 1B. The whole structure 20, 21, 22 may now be annealed in an annealer to reduce absorption losses caused by N-H bonds. A Tempress System TS-6304 can be used as annealer. As indicated in Figure 1C, a ridge 23 is now defined by means of a Reactive Ion

Etching (RIE) process. For this purpose one can use CHF_3 and O_2 as reactants. This ridge 23 is supposed to serve as waveguide channel. Now an upper cladding layer 24 is formed on top of the SiON core 22 and ridge 23. The upper cladding layer 24 comprises SiO_2 that was deposited using PECVD. Figure 1D illustrates a waveguide after this upper cladding layer 24 was deposited.

Some additional steps are required in order to form a chromium heater, for example. These additional steps are illustrated in Figures 1E - 1F. As indicated in Figure 1E, a chromium layer 25 is deposited on the upper cladding layer 24 so that it covers part of the. A sputter deposition process can be used to form the chromium layer 25. An additional aluminum layer 26 can be deposited by sputtering to form a low-resistance contact line. This is illustrated in Figure 1F.

A typical waveguide, according to the present invention, has a ridge width between $1\text{ }\mu\text{m}$ and $5\text{ }\mu\text{m}$, preferably $3\text{ }\mu\text{m}$, and a thickness between $1\text{ }\mu\text{m}$ and $3\text{ }\mu\text{m}$, preferably of $1.3\text{ }\mu\text{m}$. The original thickness of the SiON layer 22 (Figure 1B) is between $1\text{ }\mu\text{m}$ and $5\text{ }\mu\text{m}$, and preferably about $2\text{ }\mu\text{m}$. After the ridge formation this layer 22 is reduced to a thickness of about $.65\text{ }\mu\text{m}$ (Figure 1C). The SiO_2 cladding layers 21 and 24 have a refractive index of about 1.45 and the SiON core 22 has a refractive index of about 1.5. The index contrast is thus about 3.3%. The present waveguides have a propagation loss of less than 0.15 dB/cm. When using the above-described high-index-contrast silica-on-silicon integrated planar waveguide technology, waveguides can be realized that have a relatively small geometrical cross-section and a high lateral effective refractive-index contrast of 0.02 compared to standard single mode fibers.

An exemplary top-view of a tunable lens 40 is illustrated in Figure 2A. The tunable lens 40 comprises a waveguide array 39 with three ridge waveguides 30, 31, and 32. The light is channeled along these waveguides from left to right. Two chromium heaters 25 and 35 are arranged on top of the two uppermost waveguides 30, 31. The two heaters 25, 35 are connected by a first aluminum contact line 26 to a first contact pad 36. This first aluminum contact line 26 serves as a common electrode. Each of the two heaters 25, 35 also has its individual aluminum contact line 42, 43 and contact pad 37, 38. This arrangement of aluminum contact lines allows to individually drive current (I_1 , I_2) through the two heaters 25, 35. A steering unit 44 can be employed that drives the individual heaters. These heaters

25, 35 are part of the tunable lens 40 that allows to adjust the phase gradient across the different waveguides. By adjusting the phase gradient one can control the projection characteristic of the light emitted by the waveguide array 39 into a large optical free space element (not shown in Figure 2A).

5 An exemplary top-view of an input optical free space element 180 is schematically illustrated in Figure 2B. In this example, the input optical free space element 180 has one input channel 181 which guides a multiwavelength light wave towards the input optical free space element's free propagation region. In this free propagation region the light wave diverges, as indicated in Figure 2B by the four lines with arrows. This divergent beam is
10 picked up by the four waveguide channels 182 - 185 of the waveguide array 186. This waveguide array 186 is part of a tunable lens (not shown in this Figure 2B).

An output optical free space element 190 is schematically illustrated in Figure 2C. This element 190 comprises a waveguide array 196 with four channel waveguides 192 - 195, a free propagation region, and an output channel 191. A parallel or divergent beam -
15 schematically represented by four lines with arrows - transforms by superposition into a convergent beam in the output optical free space element 190 if the phase relations in the waveguides of the waveguide array 196 are set correctly. The convergent beam is then coupled into this output channel 191.

The basic principle of the present invention is now described in greater detail in
20 connection with Figures 3A and 3B. A 1x1 free-space non-blocking switch 10 is illustrated in these two Figures. Figure 3A shows the switch 10 in a first switching state (on-state) where the input side is connected to the output side. In other words, in this first switching state a multiwavelength light wave arriving via the waveguide 6 at the input side is coupled to the waveguide 7 at the output side. In a second state (off-state), the connection
25 between the waveguide 6 at the input side and the waveguide 7 at the output side is interrupted and no coupling between the two sides takes place. This second state is illustrated in Figure 3B. The switch 10, according to the present invention, comprises three optical free space elements: an input optical free space element 8, a large optical free space element 13, and an output optical free space element 9. In addition, the switch 10

comprises an input tunable optical lens 12 with an input waveguide array 11, and an output tunable optical lens 15 with an output waveguide array 14. The input optical free space element 8 sits in front of this input tunable optical lens 12 and the output optical free space element 9 follows after the output tunable optical lens 15.

- 5 A light wave 16 arriving via the input waveguide 6, the input optical free space element 8, and the input waveguide array 11 with input tunable optical lens 12 is projected into the large optical free space element 13. The input tunable optical lens 12 interacts with the input waveguide array 11 such that the light wave 16 in the large free space element 13 can be steered by adjusting the lens 12. Due to the adjustment of the lens 12 one can change the
10 projection characteristic of the input tunable optical lens 12. In Figure 3A, the input tunable optical lens 12 is adjusted such that the light wave 16 has a focal point 17 right in the middle of the large free space element 13.

- The output tunable optical lens 15 is arranged such that it is able to receive the light wave 16 from the large free space element 13, provided that its receiving characteristic is adjusted
15 accordingly. For this purpose, the output tunable optical lens 15 comprises an output waveguide array 14 and heaters that allow to adjust the receiving characteristic so as to (actively) capture the light wave 16 from the large free space element 13. As illustrated in Figure 3A, all light from the input waveguide array 11 is focussed at focal point 17 and from there captured by the output waveguide array 14. The output optical free space element 9
20 collects the light from the waveguide array 14 into the output channel 7.

In other words, light is switched from the input side to the output side.

- Turning now to Figure 3B, the same switch 10 is shown in a second state, also referred to as off-state. It is obvious that there are various other switching states. In this particular state, the input tunable optical lens 12 is adjusted such that the light wave 16 has a focal point 19 that is
25 not in the middle of the large free space element 13 anymore. The light wave 16 was tilted upwards by tuning the input tunable optical lens 12. The output tunable optical lens 15 has not been adjusted in the present example which means that the receiving characteristic remains the same. The output tunable optical lens 15 has a focal point 18. Since the focal points 18 and

19 are spaced apart, there is no (or almost no) light coupled from the input side to the output side. This explains why this state is also called off-state.

A switch in accordance with the one illustrated in Figures 3A and 3B can be used to realize an on/off switch.

5 A more sophisticated switch 50 is illustrated in Figure 4. This switch 50 (optical chip) is an $N \times N$ free-space non-blocking switch. It comprises N input channels 187, 188, 189, each having a (small) input optical free space element 181, 182, 183, and an input tunable optical lens 54, 55, 56 with input waveguide arrays 51, 52, 53. The switch 50 furthermore comprises a large free space element 60, and N output channels 190, 191, and 192. Each
10 output channel has an output tunable optical lens 61, 62, 63 with output waveguide arrays 57, 58, 59 and a (small) output optical free space element 184, 185, 186. The tunable optical lenses 54, 55, 56 on the input side and the tunable optical lenses 61, 62, 63 on the output side are adjusted such that a light wave 64 arriving via the input waveguide array 51 is focussed onto focal point 67 and then captured by the output waveguide array 58. The
15 light wave 65 is emitted by the input waveguide array 52 into the large free space element 60 and projected onto the focal point 69. The output waveguide array 59 captures the light wave 65. The light wave 66 emitted by the N -th input waveguide array 53 is focused onto the focal point 68. The output waveguide array 57 captures this light wave. Many different switching states can be obtained by tuning/adjusting the input tunable optical lens 54, 55,
20 56 and output tunable optical lens 61, 62, 63. The input side and output side of this switch 70 are symmetrical. In the present snapshot, input channel 187 is connected to output channel 191, input channel 188 is connected to output channel 192, and input channel 189 is connected to output channel 190.

Another embodiment is illustrated in Figure 5. A switch 70 is shown that comprises N
25 input channels 74 - 76, N input optical free space elements 71 - 73, and N tunable lenses 152 - 154 with N input waveguide arrays. The switch further comprises a large optical free space element 151. The switch 70 comprises N output channels 81 - 83, N output optical free space elements 77 - 79, and N tunable lenses 155 - 157 with N output waveguide arrays. In order to obtain a better separation of adjacent input and output channels (reduced

cross-talk), a filtering element 80 is placed in the middle of the free space element 151. This filtering element 80 sits where the intermediate focal plane of the switch 150 is. It comprises openings at those locations where focal points are. The input waveguide arrays create a real image of the input waveguides in the middle of the large free space element 151 exactly where the openings of the filtering element 80 are. The arrays at the output side can be tuned to actively capture light from those openings. Any higher order diffraction peaks from the waveguide arrays that hit the filtering element 80 outside the openings is suppressed by the filtering element 80. In other words, the filtering element 80 serves as an optical filter. The positions of real images in this intermediate focal plane can be calculated. In case of an $N \times N$ switch there are $2 \times N - 1$ focus points, i.e., the filtering element 80 would have $2 \times N - 1$ openings.

In the following sections, some variations or modifications of the inventive scheme are addressed. The following observations indicate how powerful and flexible the inventive scheme is. It can be used in many different applications.

In Figure 6 a symmetrical switch arrangement 90 is shown where there are $N=3$ input channels 120, 121, 122. Each input channel comprises an input optical free space element 193 and a tunable lens 205 with five waveguides 91. The switch 90 further has $M=3$ output channels 123, 124, 125. Each output channel comprises a tunable lens 206 with five waveguides 95 and an output free space element 194. The waveguides 91 and 95 are arranged with respect to the large free space element 92 such that (1) the focal points all are on the focal plane 93, and (2) such that the focal plane is in the middle of the large free space element 92. The present symmetrical switch arrangement has tunable lenses, like the other switches addressed before. Note that these tunable lenses are only schematically illustrated in Figure 6. Figure 6 represents a switch state where all tunable lenses are in their off-state, i.e., no beam steering takes place. The light beams enter the large free space element 92, are focussed onto focal points 94 and from there captured by the tunable lenses 95 at the output side. In other words, the switch routes a first light wave from the uppermost input channel 120 to the uppermost output channel 123. A second light wave is routed from the input channel 121 in the middle to the output channel 124 in the middle, and a third light wave is routed from the input channel 122 at the bottom to the output channel 125 at the bottom.

This switch 90 can now be switched into various switch states by adjusting the input tunable optical lenses and/or the output tunable optical lenses. Let us assume for the time being that just the input tunable optical lens of the uppermost input channel 120 is adjusted in order to move the focal point of the uppermost light beam upwards. With all the other
5 tunable optical lenses in the off-states this would mean that the focal point of the uppermost input channel 120 and the uppermost output channel 123 do not coincide anymore. The first light wave arriving via this channel 120 is not routed to the output channel 123. This particular optical 'link' is interrupted.

In Figure 7, an asymmetrical switch arrangement 130 is shown that has N=3 input
10 channels 140, 141, 142. Each input channel comprises an input optical free space element 195 and a tunable lens 207 with four waveguides 131. The switch 130 further has M=3 output channels 143, 144, 145. Each output channel comprises an output optical free space element 196 and a tunable lens 208 with three waveguides 135. The tunable lenses 207, 208 are arranged with respect to the large free space element 132 such that (1) the focal
15 points all are on the focal plane 133, and (2) such that the focal plane 133 is in the middle of the large free space element 132. The present switch arrangement 130 has tunable lenses 207 and 208, like the other switches addressed before. Note that these tunable lenses 207, 208 are only schematically depicted in Figure 7. All tunable lenses 207, 208 are in their off-state, i.e., no beam steering takes place. The light beams enter the large free space
20 element 132 and are focussed onto focal points 134. The receiving characteristic of the output tunable lenses 208 is adjusted such that the focal points 136 do not overlap with the focal points 134. In this switch state no light is captured by the output tunable lenses 208, i.e., the input channels 140, 141, 142 are not coupled to any of the output channels 143, 144, 145. No light travels from the left hand side to the right hand side. The optical links
25 are all interrupted.

This switch 130 can now be switched into various switch states by adjusting the input tunable optical lenses 207 or the output tunable optical lenses 208. Preferably, both the input tunable optical lenses 207 and the output tunable optical lenses 208 are adjusted so as to satisfy the criteria a) - c) for an optimal link, as defined in an earlier section of the

detailed description. Let us assume for the time being that just the output tunable optical lens 208 of the uppermost output channel 143 is adjusted in order to move the focal point upwards. With all the other tunable optical lenses in the off-state this would mean that the focal point of the uppermost input channel 140 and the uppermost output channel 143 coincide and the first
5 light wave arriving via this channel 140 is routed to the output channel 143. I.e., there exists an optical 'link' between these two channels. All the other optical links still are interrupted.

The switches 90 and 130 both can be switched by adjusting the beam direction in the large free space element.

Yet another switch design 160, according to the present invention, is illustrated in Figure 8.

10 Instead of an intermediate focal plane, the large free space element 161 has a reflective surface 162. There are two input channels 201, 202 which have input optical free space elements 197, 198, tunable lenses 163 and 164, and waveguide arrays 167, 168. Furthermore, there are two output channels 203, 204 with output optical free space elements 199, 200, tunable lenses 165 and 166, and waveguide arrays 169, 170. A first light wave arriving via the input channel 201
15 is focused onto the reflective surface 162 from where it is captured by the output channel 203. A second light wave arriving via the input channel 202 is focused onto the reflective surface 162 from where it is captured by the output channel 204. Such a switch 160 may require less space than the other switches presented herein since the size of the large free space element 161 can be reduced.

20 The preferred implementation of the present invention is illustrated in Figure 9. This switch 210 is characterized in that its input side is a mirror image of its output side. The switch 210 comprises 8 input channels 212, followed by 8 input optical free space elements 213, and 8 input tunable lenses 214 with heaters and waveguide arrays. The waveguides of these waveguide arrays are connected/coupled to a large optical free space element 211. On the
25 opposite side of the free space element 211, there are 8 output tunable lenses 215 with heaters and waveguide arrays. These 8 output tunable lenses 215 feed light into 8 output optical free space elements 216 that are coupled to 8 output channels 217. Note that the contact lines for the individual heaters are not shown in Figure 9.

The switch 210 is made using IBM's high-index-contrast silica-on-silicon integrated planar waveguide technology. The preferred dimensions for switch 210 are given on the top left-hand side of Figure 9. The input channels 212 and the output channels 217 are separated by 0.1 mm through 0.5 mm, and preferably by about 0.25 mm. The 8 input
5 optical free space elements 213 and the 8 output optical free space elements 216 each have a length of 1 mm through 0.1 mm, preferably about 0.5 mm, and a width of 1mm through 0.1 mm, preferably 0.3 mm. The large optical free space element 211, however, has a length of 10 mm through 1 mm, preferably about 4 mm, and a width of 10 mm through 0.5 mm, preferably 2.4 mm. The separation of the waveguides at the optical free space
10 elements 213, 11, and 216 is between $1\text{ }\mu\text{m}$ and $20\text{ }\mu\text{m}$, preferably about $8\text{ }\mu\text{m}$. The heater pads or lines have a length between 1 mm and 10 mm, preferably about 2 mm. The pads are separated between $50\text{ }\mu\text{m}$ and $500\text{ }\mu\text{m}$, preferably by about $100\text{ }\mu\text{m}$. The separation of the individual heater arrays is between $100\text{ }\mu\text{m}$ and 0.1 mm, preferably about $400\text{ }\mu\text{m}$.

IBM's high-index-contrast silica-on-silicon integrated planar waveguide technology allows
15 to make waveguides with small bending radii and the switch design can be further optimized to reduce the lateral size.

By slightly defocusing the tunable lens on the input side and/or the tunable lens on the output side, the power throughput to the output channel can be varied without introducing crosstalk to other channels. The present switches thus can also be used to adjust the power
20 in the output channels. The heater steering unit may comprise a unit that allows the adjustment of the power in the output channel.

The number of input channels does not have to be equal to the number of output channels. The number of waveguides per waveguide array does not have to be the same on the input side and output side. It is also conceivable that there are a few input channels with five
25 waveguides and a few input channels with six waveguides, for example.

It is possible to use two heaters per waveguide array: one to apply linear phase gradients to adjust the distance of the projected light wave and one to apply quadratic or higher order phase gradients to adjust the focal length of the projected light wave.

The fewer heaters one uses the less complex the heater steering unit and switch control box becomes.

5 The present switch may comprise one or more coupling elements. A v-shaped groove, for example, may serve as a coupling element. Such an element allows the butt-coupling of a fiber to one of the input channels or output channels.

The present switch is well suited for integration with a large number of other components on a chip. The switches, according to the present invention, provide the high functionality which will be required by future telecommunication networks.

10 The present invention can be integrated into multiwavelength telecommunication data transmission systems.

CLAIMS

1. Optical switch (10; 50; 70; 90; 130; 160; 210) integrated into a substrate, comprising
 - an input channel (6; 74-76; 120-122; 140-142; 187-189; 201-202; 212) with an input optical free space element (8; 71-73; 181-183; 193; 195; 197-198; 213),
 - 5 • a large optical free space element (13; 60; 151; 100; 161; 211),
 - an input tunable optical lens (12; 54-56; 205; 207; 152-154; 163-164) with adjustable projection characteristic for projecting a light wave (16; 64-66) received from the input optical free space element (8; 71-73; 181-183; 193; 195; 197-198; 213) into the large free space element (13; 60; 151; 100; 161; 211),
 - 10 • an output channel (7; 81-83; 190-192; 123-125; 143-146; 203-204; 217) with an output optical free space element (9; 77-79; 184-186; 194; 196; 199-200; 216), and
 - an output tunable optical lens (15; 61-63; 155-157; 165-166; 206; 208) with adjustable receiving characteristic for capturing the light wave (16; 64-66) from the large free space element (13; 60; 151; 100; 161; 211) and for feeding the light wave
 - 15 (16; 64-66) to the output optical free space element (9; 77-79; 184-186; 194; 196; 199-200; 216).
2. The switch (10; 50; 70; 90; 130; 160; 210) of claim 1, wherein the projection characteristic is adjustable by adjusting the direction or focal length of the light wave (16; 64-66) in the large free space element (13; 60; 151; 100; 161; 211).
- 20 3. The switch (10; 50; 70; 90; 130; 160; 210) of claim 1, wherein the receiving characteristic is adjustable by adjusting the direction or focal length of the output tunable optical lens (15; 61-63; 155-157; 165-166; 206; 208).
4. The switch (10; 50; 70; 90; 130; 160; 210) of claim 1, wherein the input tunable optical lens (12; 54-56; 205; 207; 152-154; 163-164) comprises an input waveguide
- 25 array (11; 51-53; 91; 131; 167-168).

5. The switch (10; 50; 70; 90; 130; 160; 210) of claim 1, wherein the output tunable optical lens (15; 61-63; 155-157; 165-166; 206; 208) comprises an output waveguide array (14; 57-59; 95; 135; 169-170).
6. The switch (10; 50; 70; 90; 130; 160; 210) of claim 4 or 5, wherein the waveguide array (11; 51-53; 57-59; 91; 131; 95; 135; 167-170) comprises ridge waveguides with a waveguide core (22) and two claddings (21, 24).
7. The switch (10; 50; 70; 90; 130; 160; 210) of claim 6, wherein the waveguide core (22) comprises SiON and the two claddings (21, 24) comprise SiO₂.
8. The switch (10; 50; 70; 90; 130; 160; 210) of claim 6, wherein the ridge waveguide has a thickness between 1 μm and 3 μm , preferably of 1.3 μm , and a ridge width between 1 μm and 5 μm , preferably 3 μm .
9. The switch (10; 50; 70; 90; 130; 160; 210) of claim 1, wherein the input tunable optical lens (12; 54-56; 205; 207; 152-154; 163-164) and/or the output tunable optical lens (15; 61-63; 155-157; 165-166; 206; 208) comprise tunable heaters (40).
10. The switch (10; 50; 70; 90; 130; 160; 210) of claim 9, wherein the tunable heaters (40) comprise chromium pads or lines that are placed on top of those waveguide arrays where a phase gradient is to be adjusted.
11. The switch (10; 50; 70; 90; 130; 160; 210) of claim 9, wherein a linear phase gradient between the light waves traveling in the different waveguides of the waveguide array is obtainable if a current is driven through the tunable heaters (40).
12. The switch (10; 50; 70; 90; 130; 160; 210) of claim 9, wherein a non-linear phase gradient between the light waves traveling in the different waveguides of the waveguide array is obtainable if a current is driven through the tunable heaters (40).
13. The switch (70) of claim 1, comprising a filtering element (80) with openings.
14. The switch (70) of claim 13, wherein the filtering element (80) is placed at the large free space element's intermediate focal plane.

15. The switch (10; 50; 70; 90; 130; 160; 210) of claim 1, comprising N input channels (6; 74-76; 120-122; 140-142; 187-189; 201-202; 212) and M output channels (7; 81-83; 190-192; 123-125; 143-146; 203-204; 217), with N and M being integer numbers.
- 5 16. The switch (70; 90; 130) of claim 15, comprising N input optical free space elements (8; 71-73; 181-183; 193; 195; 197-198; 213) and M output optical free space elements (9; 77-79; 184-186; 194; 196; 199-200; 216).
17. The switch (10; 50; 70; 90; 130; 160; 210) of claim 1 being produceable using an integrated planar waveguide technology.
- 10 18. The switch (10; 50; 70; 90; 130; 160; 210) of claim 1 being designed for use in the optical transmission window, i.e., in a wavelength range between 1540 nm and 1570 nm.
19. The switch (10; 50; 70; 90; 130; 160; 210) of claim 9, comprising a heater steering unit (44).
- 15 20. The switch (10; 50; 70; 90; 130; 160; 210) of claim 19, wherein the heater steering unit (44) comprises a current source or a voltage source.
21. The switch (10; 50; 70; 90; 130; 160; 210) of claim 19, wherein the heater steering unit (44) comprises a microcomputer to store settings of the tunable heaters (40).
- 20 22. The switch (10; 50; 70; 90; 130; 160; 210) of claim 19, wherein the heater steering unit (44) comprises a unit for the adjustment of the power captured by the output tunable optical lens (15; 61-63; 155-157; 165-166; 206; 208), by defocusing the input tunable optical lens (12; 54-56; 205; 207; 152-154; 163-164) and the output tunable optical lens (15; 61-63; 155-157; 165-166; 206; 208).

23. The switch (10; 50; 70; 90; 210) of claim 1, wherein the input tunable optical lens (12; 54-56; 205; 207; 152-154; 163-164) is a mirror image of the output tunable optical lens (15; 61-63; 155-157; 165-166; 206; 208).
24. The switch of claim 1, comprising a coupling element which allows the butt-coupling
5 fibers to one of the input channels (6; 74-76; 120-122; 140-142; 187-189; 201-202; 212) and/or output channels (7; 81-83; 190-192; 123-125; 143-146; 203-204; 217).
25. Non-blocking free-space switch comprising a switch according to any of the claims 1 through 24.
26. The non-blocking free-space switch of claim 25, comprising a switch control box or a
10 computer interface.
27. Data transmission systems comprising a switch according to any of the claims 1 through 24.