Silicon-on-Insulator Ultra-Compact Duplexer based on a Diffractive Grating Structure

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Abstract: The use of a silicon-on-insulator diffractive grating structure is proposed to achieve ultra-compact duplexing operation. One-dimensional grating structures are proposed to spatially separate two wavelength bands. This device can become a key component in the fabrication of integrated optical transceivers for fiber-to-the-home applications, where a 1310nm wavelength channel and a 1490nm wavelength channel need to be duplexed. A 10µm x 10µm one-dimensional grating structure allows to spatially separate both wavelength bands on the photonic integrated circuit, with an average coupling efficiency of 55% and an optical bandwidth of 55-60nm. While these one-dimensional grating structures are strongly polarization dependent, a two-dimensional grating structure is presented to achieve polarization independent operation.

OCIS codes: (130.0130) Integrated Optics; (050.2770) Gratings

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1. Introduction

Silicon-on-insulator (SOI) is a promising platform for high-density integrated optics due to the large refractive index contrast between the silicon waveguide core (n_{Si}=3.45) and the SiO_2 cladding (n_{SiO2}=1.45). Due to this high refractive index contrast, sharp waveguide bends, small wire pitches and compact high-Q cavities can be made [1,2]. These structures can moreover be fabricated using standard complementary metal oxide semiconductor (CMOS) technology, improving the performance, yield and reproducibility, while reducing the cost of the integrated circuits due to economies of scale. A drawback of the high refractive index contrast is the severe mismatch between the size of the SOI waveguide mode and that of a single mode optical fiber, making efficient coupling of light between the optical fiber and the SOI waveguide circuit a nontrivial task. Fiber-to-waveguide diffractive grating couplers have been proposed to achieve the efficient coupling of light from an SOI high index contrast waveguide to a single mode fiber and vice versa [3,4]. They have the advantage of being very compact and they do not require a polished facet to couple light into the photonic integrated circuit, paving the way to wafer-scale testing and easy packaging of the photonic integrated circuits. Although the use of high index contrast gratings allows a 3dB optical coupling bandwidth on the order of 50-100nm, there are applications which require a larger optical coupling bandwidth, especially because of the fact that light in two distinct (and widely separated) wavelength bands needs to be processed by the photonic integrated circuit. An important application satisfying this description is the use of integrated transceivers for fiber-to-the-home (FTTH) optical networks [5], in which at the subscriber side a 1310nm wavelength is used to transmit upstream data over the network, while a 1490nm downstream optical signal needs to be processed (and vice versa at the central office side). As the wavelength span required in this application exceeds the optical bandwidth of the fiber-to-waveguide grating coupler, an alternative approach is needed, which increases the effective wavelength span, while maintaining the advantage of being compact and allowing wafer-scale testing and ease of packaging. Therefore, in this paper the use of a grating coupler is extended to allow operation in two distinct wavelength bands. Moreover, while both wavelength bands will be efficiently coupled into or out of the photonic integrated circuit, they will be spatially separated on the photonic integrated circuit, thereby at the same time performing fiber-to-chip coupling and duplexing operation.

2. Proposed duplexer structure

The proposed grating coupler structure to achieve duplexing operation of two widely spaced wavelength bands is presented in figure 1. It consists of a one-dimensional grating structure defined on a silicon-on-insulator waveguide platform, while the fiber is tilted by an angle θ with respect to the vertical axis. While in standard fiber-to-waveguide grating couplers only one access waveguide is used, in this duplexer structure both access waveguides are used to expand the wavelength range over which light can be efficiently coupled between the photonic integrated circuit and a single mode optical fiber. At the same time duplexing operation for wavelength band λ_1 and λ_2 is achieved as shown in figure 1. The grating is constructed by locally defining an additional silicon overlay (either by epitaxial growth of silicon or by chemical vapor deposition of poly-crystalline silicon) after which the grating is defined by etching a one-dimensional array of slits in the layer stack. As was shown in [6], this device geometry allows an important increase in fiber coupling efficiency compared to the case of directly etching a grating structure in the silicon waveguide core layer. Although these devices can be designed to allow duplexing operation for a wide variety of wavelength band combinations, in this paper, the particularly important application of duplexing a 1310nm wavelength channel and a 1490nm wavelength channel, for use in fiber-to-the-home transceivers, will be discussed. Several parameters of the proposed grating structure need to be optimized to achieve optimal duplexing operation for these envisioned wavelength bands, including the silicon overlay thickness, the grating etch depth, the grating period and grating duty cycle, the number of grating periods, the tilt angle of the optical fiber and its optimal position with respect to the grating. A 220nm thick silicon waveguide core on top of a 2μm buried oxide layer is assumed. In this analysis, only TE-polarized light will be considered. Although the proposed one-dimensional grating duplexer is very polarization dependent, a two-dimensional grating duplexer structure [3] can be used to achieve polarization independent operation as will be shown in section 3. The grating etch depth is fixed in this paper to 220nm, in order for the grating definition to be compatible with the etching of the SOI waveguide structures (etched completely through the 220nm silicon waveguide core), thereby reducing the amount of processing steps required for the definition of the ultra-compact duplexer structure. For the simulations, a two-dimensional vectorial eigenmode expansion tool with perfectly matched layer absorbing boundary conditions was used (CAMFR) [7]. The dispersion of the material refractive index was taken into account. The silicon overlay thickness and the grating duty cycle were optimized in order to maximize the average grating directionality (being the fraction of optical power diffracted upwards by the

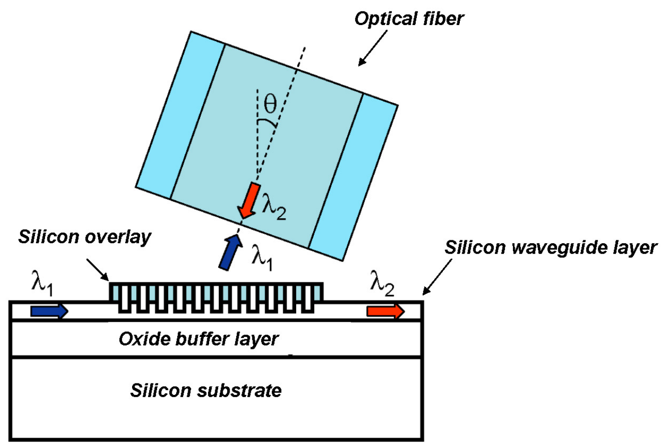

Fig. 1. Proposed design of an ultra-compact wavelength duplexer based on diffractive fiber-to-waveguide grating couplers

grating to the total diffracted power when excited from the SOI waveguide) for the 1310nm wavelength channel and the 1490nm wavelength channel. This led to an optimal grating overlay thickness of 140nm and a grating duty cycle (defined as the ratio of the slit width to the grating period) of 60 percent. The average grating directionality is higher than 80 percent, similar to the results obtained in previous work [6]. The grating period and tilt of the single mode optical fiber was determined by plotting the diffraction angle of light with a wavelength of 1310nm (1490nm) in the air superstrate, when exciting the grating from the left hand side (right hand side). The results are plotted in figure 2, showing that for a grating period of 520nm, both wavelengths have an identical diffraction angle of 14.3 degrees. By placing the fiber under this angle with respect to the vertical axis and applying this grating period, duplexing operation is achieved.

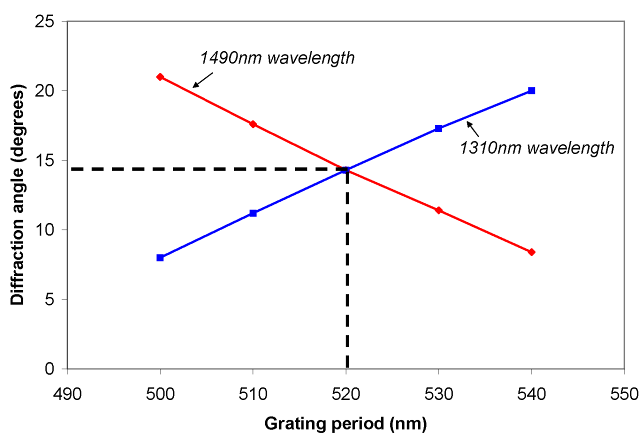

Fig. 2. Diffraction angle of light with a wavelength of 1310nm (1490nm) exciting the grating from the left hand side (right hand side). The intersection of both curves determines the working point for duplexer operation.

A final set of parameters to optimize is the extent of the grating (the number of grating periods) and the position of the optical fiber with respect to this grating. A single mode fiber with a mode field diameter ($1/e^2$ intensity width) of 10.4µm was assumed. In figure 3, the average fiber coupling efficiency of the 1310nm wavelength channel and the 1490nm wavelength channel is plotted for different grating lengths (expressed by the number of grating periods), as a function of the position of the centerline of the optical fiber (indicated by the dashed line in figure 1) with respect to the left hand side edge of the silicon overlay. The coupling efficiency to optical fiber was assessed by exciting the grating structure from the respective access waveguides with the power normalized fundamental SOI waveguide mode (for the respective wavelengths of 1310nm and 1490nm) and by calculating the diffracted field $\boldsymbol{E}_{diff}$ at a distance above the diffraction grating for both wavelengths. The fiber coupling efficiency η for the respective wavelength channels is then obtained by evaluating the overlap integral

$$\eta = \left| \int \boldsymbol{E}_{diff} \times \boldsymbol{H}_{fib}^{\ *} \cdot \boldsymbol{dn} \right|^2 \tag{1}$$

in which $\boldsymbol{H}_{fib}$ is the magnetic field of the Gaussian fiber mode, which is also normalized in power. $\boldsymbol{dn}$ lies along the surface normal of an integration path in the air cladding which spans the complete grating coupler length. This overlap integral is evaluated for both wavelength channels, while varying the fiber centerline position, leading to the average fiber coupling efficiency as a function of fiber position and grating length, as plotted in figure 3.

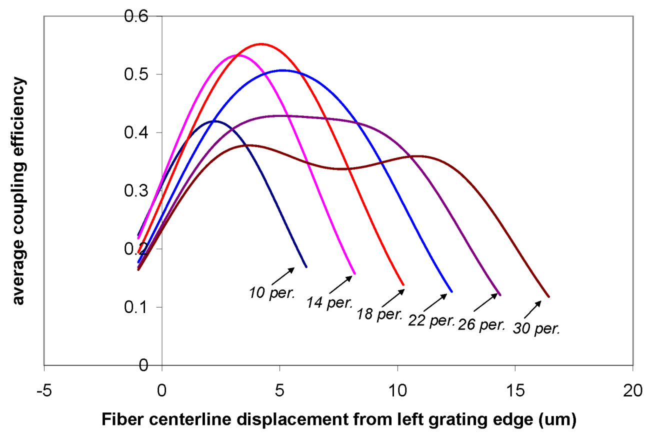

Fig. 3. Average fiber coupling efficiency of both wavelength channels as a function of the number of grating periods and the position of the optical fiber

From this simulation we can conclude that there exists an optimum grating length (corresponding to 18 grating periods) and fiber position, for which the average fiber coupling efficiency is maximal. The fiber-to-grating 1dB alignment tolerance is about ±1.5µm, which is sufficient for practical applications. The optical bandwidth of the ultra-compact duplexer was assessed by two-dimensional FDTD simulation, in which the fiber-to-waveguide coupling efficiency of the optimized device was calculated by illuminating the duplexer structure with the optical fiber mode. The resulting coupling efficiency spectrum into the respective waveguides is depicted in figure 4. This coupling spectrum shows a 3dB optical bandwidth of 55nm (60nm) for the 1310nm (1490nm) wavelength channel. The crosstalk between both wavelength channels is below -20dB. A plot of the electric field distribution of the duplexer grating structure, when illuminated from an optical fiber, is shown in figure 5, clearly illustrating the duplexing behavior of the diffractive grating structure (for both wavelength channels). When using the diffractive grating structure in a transceiver application, in which one wavelength channel is used for upstream optical data transport (λ_1 in figure 1) while the other wavelength channel is used for downstream optical data transport (λ_2 in figure 1), crosstalk can have a different origin compared to the case where both wavelength channels are used for downstream data transport (as was the case in figure 4 and 5). This is illustrated in figure 6a for an upstream wavelength λ_1 and downstream wavelength λ_2, while the simulated

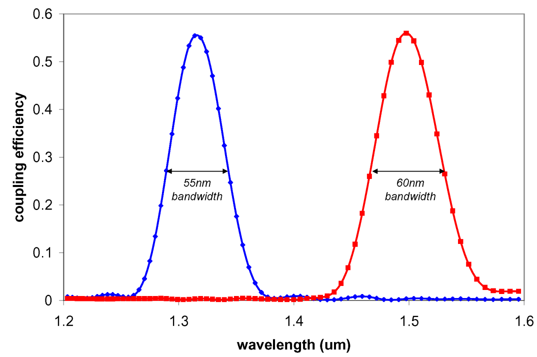

Fig. 4. Coupling efficiency spectrum for both wavelength channels for the optimized duplexer grating

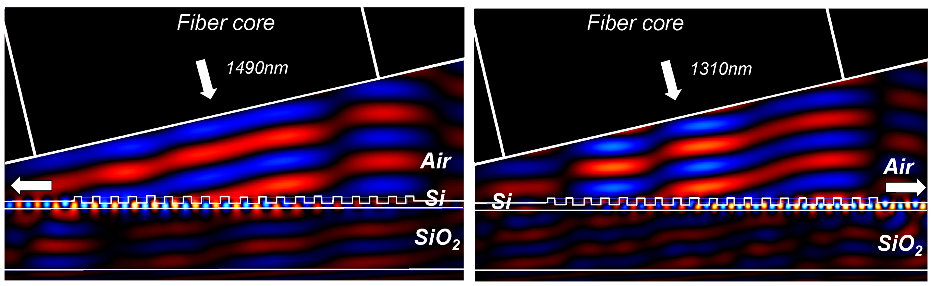

Fig. 5. Electric field plot of the duplexer grating structure when illuminated from an optical fiber for both wavelength channels, illustrating the duplexing behavior.

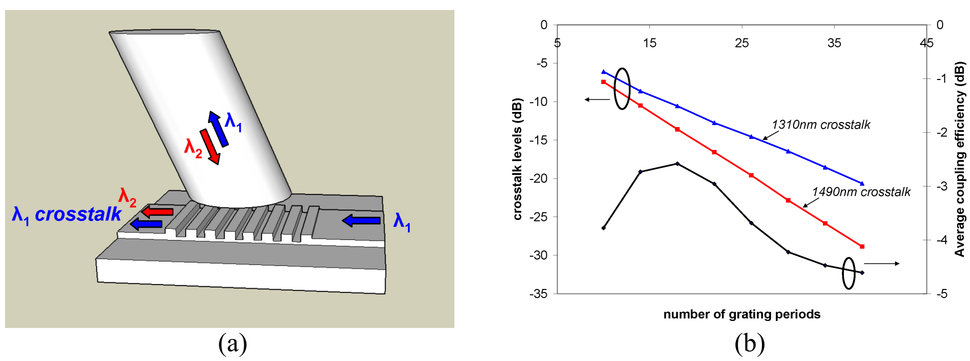

Fig. 6. Origin of crosstalk when using this duplexer structure in transceiver configuration (a) and the influence of the grating length on crosstalk and average fiber coupling efficiency (b)

crosstalk as a function of grating length (number of grating periods) is plotted in figure 6b, both for using the 1310nm wavelength channel and the 1490nm wavelength channel as upstream channel (1310nm is used at the subscriber side, 1490nm is used at the central office side). The average fiber coupling efficiency is also plotted. From this simulation, it is clear that sufficiently low crosstalk levels can only be obtained for long gratings, at the expense of a reduction in average fiber coupling efficiency. An alternative solution implies working in the optimum average coupling efficiency point (18 grating periods), while implementing an SOI waveguide bandstop filter in the downstream path to improve the crosstalk performance of the device. While the previously presented results originated from two-dimensional simulations, a correction factor ξ was applied to correct this two-dimensional fiber coupling efficiency for the mismatch between the lateral Gaussian fiber mode profile and the SOI waveguide mode profile, namely the overlap integral between these lateral mode profiles (ξ=0.97).

3. Polarization insensitive duplexing operation

As in the previously discussed case of a one-dimensional grating structure the behavior of the grating structure is very different for TE and TM polarization, a two-dimensional grating structure is required to achieve polarization independent operation by using a polarization diversity scheme [3]. The layout of the two-dimensional grating duplexer is depicted in figure 7. It consists of a two-dimensional square lattice diffraction grating, defined at the intersection of four access waveguides. The operation principle is clear from this figure: the two orthogonal polarization states of light in the optical fiber are coupled via the diffraction grating into the TE-polarized modes of the SOI access waveguides and this for both wavelength channels (in order not to overload the figure, only the downstream wavelength polarization is plotted). In order to achieve duplexing operation, the optical fiber is tilted along the symmetry axis of the grating structure (indicated by the dashed line in figure 8). By connecting identical optical circuits to the access waveguides (identical circuits per wavelength channel), polarization insensitive duplexing operation through polarization diversity can be obtained.

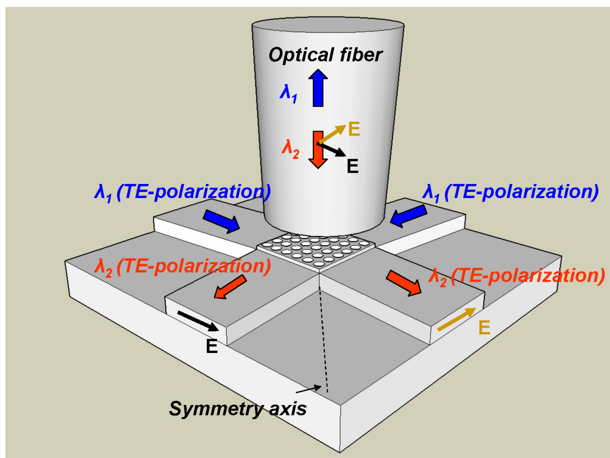

Fig. 7. Layout of the grating duplexer structure for polarization diversity operation

4. Conclusions

In this paper, an ultra-compact duplexer based on a diffractive grating structure on a silicon-on-insulator waveguide platform was described. While a one-dimensional grating structure can be used to achieve duplexing operation for a single polarization, a polarization insensitive duplexer circuit is proposed based on a polarization diversity scheme. This device can become a key component in the fabrication of integrated optical transceivers for fiber-to-the-home applications, as low cost is a critical factor there, which can be achieved by exploiting the economy of scale of waferscale processing of silicon-on-insulator photonic integrated circuits using standard CMOS technology.

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