

A compact bi-wavelength polarization splitting grating coupler fabricated in a 220 nm SOI platform

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Abstract: We experimentally demonstrate a polarization splitting grating coupler that is operational near 1310 nm and 1550 nm in a silicon-on-insulator platform, using the same fiber angle for both wavelength bands. At 1550 nm, the device has an insertion loss of 7.1 dB and a 1.5-dB transmission window of 35 nm. At 1310 nm, the insertion loss and 1.5-dB transmission window are 8.2 dB and 18 nm, respectively. Polarization isolation at 1550 nm is 24 dB. This is the first experimental demonstration of a bi-wavelength polarization-splitting grating coupler.

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1. Introduction

Silicon is an attractive platform for developing highly integrated optical devices. The high index contrast of silicon and silicon dioxide enables the confinement of light to sub-micron waveguides [1]. Furthermore, the fabrication infrastructure is relatively mature since the tools and processes that are used to fabricate optical devices in silicon are the same as those used in the microelectronics industry [2]. There are several platforms in both industry [3, 4] and publicly available [5, 6], with devices that modulate and detect light fabricated on the same wafer in a single process flow. This high level of integration supports the design and production of optical systems that may have been too costly or complex to be developed and packaged in other material systems [7, 8]. In particular, the relatively high cost and complexity of wavelength division multiplexed (WDM) passive optical network (PON) solutions for fiber-to-the-home (FTTH) present an attractive area in which silicon-based photonics can excel.

One important design consideration in a silicon WDM PON system is the coupling of light from a single mode fiber to on-chip waveguides. Since typical systems operate at two wavelengths near 1310, 1490, or 1550 nm it is necessary to design devices that can efficiently

couple in at least two of these bands. Typical grating couplers used for this application have two primary drawbacks: sensitivity to input polarization state and relatively narrow bandwidths. Standard single-polarization grating couplers have been demonstrated in an SOI platform to couple a single polarization state into a waveguide mode with losses as low as 1.2 dB using an apodized grating coupler [9].

To address these two issues, there have been several promising demonstrations of grating devices to couple from orthogonal polarization states as well as separate devices with transmission in 2 or more wavelength bands [10, 11]. Either 1-D or 2-D grating coupler designs are implemented in order to couple orthogonal polarizations into on-chip waveguides. Roelkens et al. also presented a theoretical bi-wavelength polarization splitting grating coupler (PSGC) by overlaying two 1-D structures into a 2-D arrangement [12].

1-D grating structures operate by coupling incident light into a forward-propagating waveguide TE_0 mode and reverse-propagating TM_0 mode. 1-D PSGCs have been reported with transmission efficiencies as high as 3 dB near 1310 nm on a 220 nm SOI wafer with a polysilicon overlay [11], and as high as 3.8 dB in 260 nm SOI without the use of polysilicon [13]. Backside metal mirrors can be further used to improve coupling efficiency [14]. In contrast to 1-D PSGC structures, 2-D PSGCs couple light from orthogonal polarization states into the same waveguide mode. Insertion losses of up to 5.7 dB have been demonstrated in 220 nm SOI [15, 16], with lower insertion losses demonstrated in 300 nm SOI compact focusing designs [3]. Alternative fabrication techniques have also been explored, such as two-layer and double corrugated PSGCs [17, 18].

Similarly, bi-wavelength grating couplers have been proposed and demonstrated using both 1-D and 2-D grating arrangements. A 1-D device with efficiency as high as 2.5 dB has been demonstrated in the 1310 nm and 1490 nm bands [11]. A 2-D single-polarization grating coupler for the 1310 and 1490 nm bands with -7 and -8 dB loss, respectively, was also demonstrated [19]. Finally, Xu et al. presented a 2-D bi-wavelength grating coupler for the 1490 and 1550 nm wavelengths with -6 and -6.5 dB insertion loss, respectively [10, 20].

In addition to single grating coupler structures to duplex light, it is also possible to use a PSGC followed by a filter such as an arrayed waveguide grating to implement polarization-insensitive duplexing of light [21-23]. However, for systems such as FTTH where the upstream/downstream wavelengths are sufficiently spaced (for example, 1310 nm and 1550 nm), the limited bandwidth of a single-wavelength grating coupler will prevent the use of this type of solution. Doerr et al. presented one solution using the Γ -M and Γ -X axes of a photonic crystal structure, allowing for polarization insensitivity near 1270 nm while still allowing a single polarization of 1577 nm light to couple on chip [24]. Instead, here we present a grating coupler device that is polarization insensitive in both the 1550 and 1310 nm transmission windows. The device achieves -7.1 dB insertion loss near 1550 nm and -8.2 dB insertion loss near 1310 nm.

2. Bi-wavelength polarization splitting design

The bi-wavelength PSGC consists of a symmetric lattice of scattering elements. An optical fiber is placed along the symmetry axis and tilted along this axis to reduce back reflection. The design process for this grating coupler can be broken down into two steps: The design of a single-polarization bi-wavelength grating coupler to define the grating pitch and duty cycle, and the overlap of two single-polarization devices in order to achieve a polarization splitting action.

A single polarization focusing grating coupler for light with free space wavenumber k_0 will have gratings defined by the phase matching condition [25]:

$$k_0 n_{eff} = k_0 n_c \sin(\theta) \cos(\phi) + \frac{2\pi}{\Lambda} \quad (1)$$

where n_{eff} is the effective index of the waveguide mode, n_c is the index of the oxide cladding, θ is the angle of the fiber measured from the normal to the chip, ϕ is the angle between the axis of the fiber and that of the output waveguide, and Λ is the pitch of the gratings. In order to achieve bi-wavelength performance the angle of the fiber and the pitch of the gratings are adjusted to satisfy the above phase matching condition for 1550 and 1310 nm light.

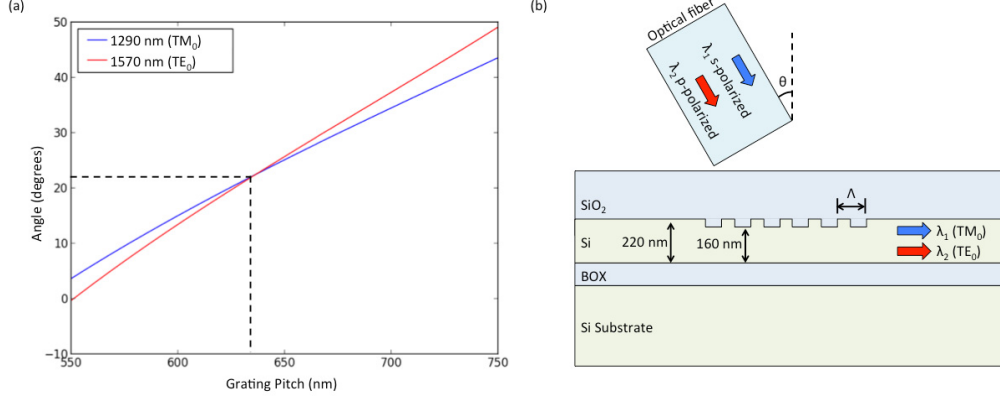


Fig 1. (a) Phase matching condition for the TM_0 mode at 1290 nm and TE_0 mode at 1570 nm. The optimum grating pitch and fiber angle is 636 nm and 22.5° , respectively. (b) Schematic illustration of a 1-D device (not to scale).

For 220 nm thick silicon, the effective indices of the 1550 TE_0 and 1310 TM_0 slab modes are very near one another: 2.85 and 2.41, respectively. This enables the phase matching condition to be met within achievable grating pitches and fiber angles. Solving Eq. 1 for these conditions at 1550 nm and 1310 nm yields an optimum grating pitch of 550 nm and fiber angle of 1.4° . These conditions are not ideal for two reasons. First, since a 550 nm grating pitch will yield features that are very close to the design rules of the process, this pitch may have problems yielding well-defined features. Secondly, the steep fiber angle may result in additional back-reflection. Instead, we have elected to design the device to couple light centered at 1570 nm and 1290 nm. Shown in Fig. 1(a) is the phase matching condition for these wavelengths, where the optimum grating pitch and fiber angle is 636 nm and 22.5° , respectively. Note that since the fiber illuminates the device through a layer of oxide cladding, we have applied Snell's law to calculate the fiber angle. Fig. 1(b) illustrates the operation of the device in one dimension.

In order to conserve space on the wafer, it is ideal to change the shape of the grating couplers to focus light into a waveguide and avoid the need to use long adiabatic tapers from the fiber mode to the waveguide mode. The expansion of the single polarization grating coupler into a focusing device may be performed by assuming that the input light consists of circular wavefronts. Defining the z-axis to be along the output waveguide and the x-axis to be the lateral direction in the plane of the wafer, we may rearrange Eq. 14 of [26] into rectangular coordinates to calculate the positions of the gratings:

$$z(x)^2 = \frac{\gamma^2 + 1}{(1 + \gamma)^2} z_0^2 + \frac{1}{\gamma^2 - 1} x^2 \quad (2)$$

where z_0 is the position of the grating at $x = 0$. This equation defines a family of confocal ellipses with eccentricity $\gamma = (n_c / n_{eff}) \cdot \sin(\theta)$.

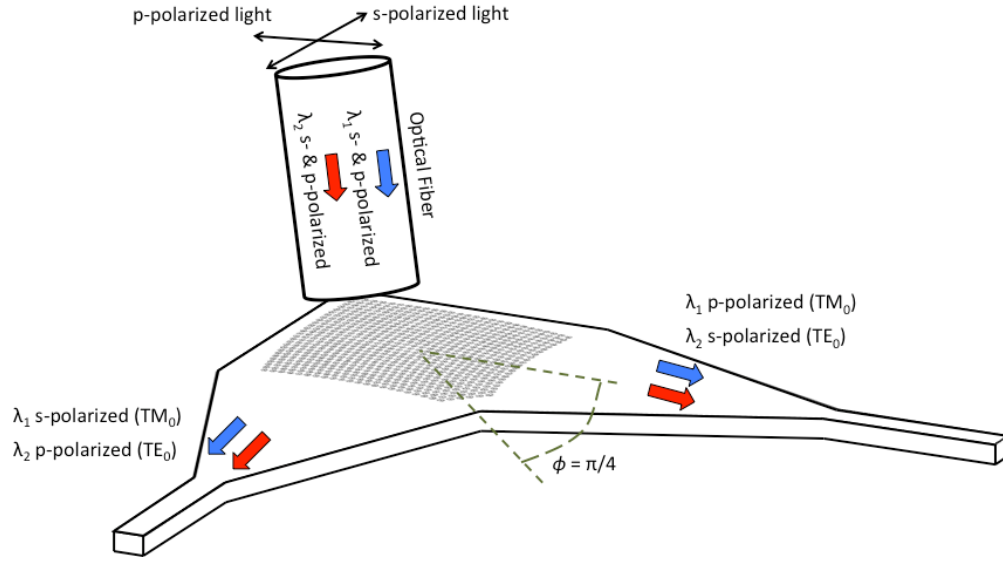


Fig. 2. Schematic illustration of the bi-wavelength polarization splitting grating coupler (not to scale). Two sources in different wavelength bands and random polarizations are input into the fiber. Light in the first wavelength band is split according to polarization and coupled into the waveguide TM_0 mode. Similarly, light in the second wavelength band is split according to polarization and coupled into the waveguide TE_0 mode.

The single polarization device may be extended to act as a polarization splitting device by superimposing two identical grating couplers rotated away from each other by 90° . Rather than continuous gratings, scattering elements are placed at the intersection points of the gratings of the two single-polarization grating couplers. The fiber is tilted along the axis of the bisector angle of the two output waveguides and the optical mode is tilted by 45° . Since the two overlaid grating couplers are oriented 90° from one another, they each couple orthogonal input polarization states from one another. Due to symmetry, the device will couple into the same waveguide mode for each input fiber polarization. Thus, the output of each waveguide will be a function of the input polarization state. Fig. 2 shows a schematic illustration of the bi-wavelength PSGC device.

It is important to note that since the fiber is no longer aligned to the output waveguide, there must be slight adjustments in the phase matching condition and the focusing design [3]. First, the parameter ϕ in Eq. 1 is now $\pi/4$ to account for the fiber orientation. This shifts the theoretical optimum fiber angle for our design to 33° . Secondly, the eccentricity of the focusing design now also has an additional factor of $\sin(\pi/4)$. Finally, the shape of the scattering elements has a large effect on polarization dependent losses. Thus, we have elected to use a rounded diamond-like pattern similar to that used in [3], which was found to perform better than purely circular scatterers.

Fig. 3 presents 3-D finite difference time domain (FDTD) simulations for the device performed in Lumerical FDTD. In the FDTD simulation, the grating coupler is illuminated by an optical fiber oriented along the symmetry axis of the device. Perfectly matched layer absorbing boundary conditions were used. Two simulations were performed—one where the electric field of the source is parallel to the output waveguide (TM_0 -coupled), and the other where the electric field is perpendicular (TE_0 -coupled). Coupling efficiency is measured from the fiber output to the waveguide TE_0 and TM_0 modes.

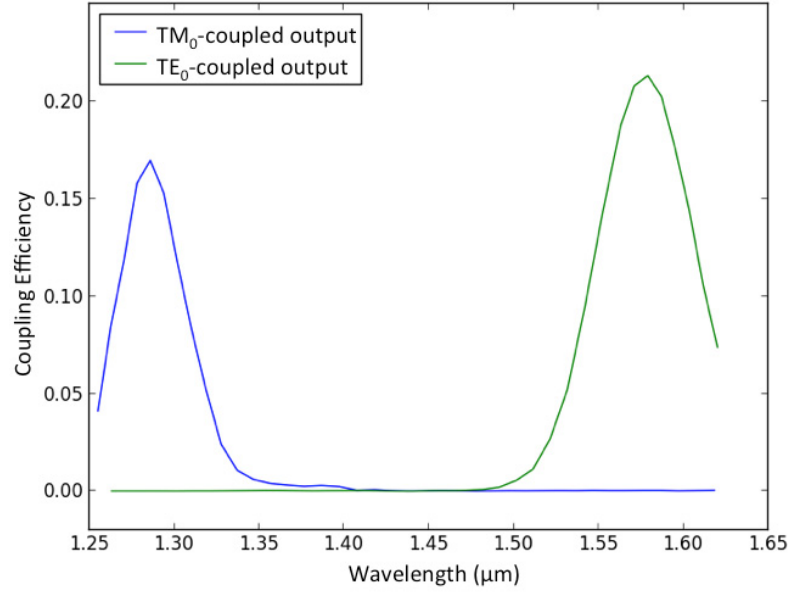


Fig. 3. 3D FDTD simulation of the coupling efficiency of the PSGC performed in Lumerical FDTD. Light in the wavelength band near 1.3 μm couples into the waveguide TM_0 mode, while light in the 1.55 μm band couples into the waveguide TE_0 mode.

3. Fabrication and Testing

Fabrication of these devices was performed at the Institute of Microelectronics (IME), A*STAR, Singapore [27] in a multi-project wafer run through the OpSIS foundry service [5]. The starting material was a 20 mm SOI wafer with 220 nm top silicon and 2 μm buried oxide thicknesses. First, a 60 nm etch was performed to define the grating trenches. Subsequent etch steps removed the unwanted silicon in order to define the output ridge waveguides and output taper. Lastly, 2.1 μm of oxide was deposited on top of the wafer. In all cases, 248 nm lithography was used. Fig. 4 shows an optical micrograph of the fabricated device as well as a rendering of a section of the device layout.

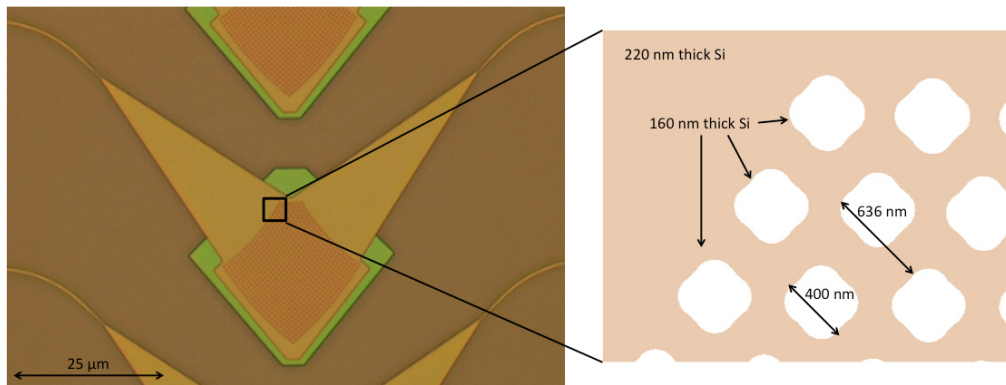


Fig. 4. Optical micrograph image of the fabricated device. Inset is a rendering of a section of the device layout. The scattering elements consist of rounded diamond-like 60 nm deep trenches in the 220 nm top silicon layer.

In order to efficiently test the device, an array of polarization maintaining (PM) fibers with a pitch of $127\ \mu\text{m}$ was used. The fast and slow axes of the PM fiber were oriented at a 45° angle in order to test the efficiency of a single polarization channel at a time. The fiber array arrangement is shown in Figs. 5(a)-5(c). The test setup and circuit arrangement shown in Figs. 6(a) and 6(b) is designed to correspond to this fiber array. In this circuit, light is input into the center device and output from identical devices on the left and right. The wavelength and input polarization is varied and the corresponding output on the outer two grating couplers is measured.

In order to first align the fiber array to the device, the fiber array position is swept across the surface of the device and then moved to the position of maximum power transmission. At this point, no further positions of either the device or the fiber array are changed in order to measure polarization-dependent loss as well as wavelength-dependent loss. To test PDL, an Agilent 8169A polarization controller is placed before the input fiber in the fiber array and an internal half-wave plate is used to vary the input polarization state into the center PSGC. The output is measured from the two output PSGCs at each input polarization.

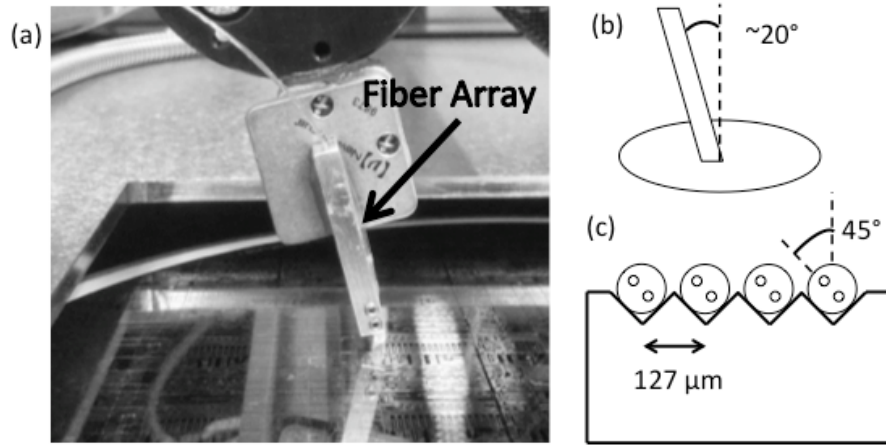


Fig. 5. (a) An array of polarization-maintaining fiber from PLC Connections is mounted above the wafer. (b) The grating coupler is designed for a fiber angle of 23° . (c) The fibers are mounted such that the fast and slow axes are rotated 45° from vertical.

4. Results and Discussion

The performance of the device is shown in Fig. 7. Maximum transmission is measured to be $-7.1\ \text{dB}$ at $1576\ \text{nm}$ and $-8.2\ \text{dB}$ at $1296\ \text{nm}$. The $-1.5\ \text{dB}$ transmission windows are $18\ \text{nm}$ and $35\ \text{nm}$ for light near 1310 and 1550 , respectively. Within the $-1.5\ \text{dB}$ window, the difference in transmission between s-polarized light and p-polarized light is less than $1\ \text{dB}$ for both wavelength bands.

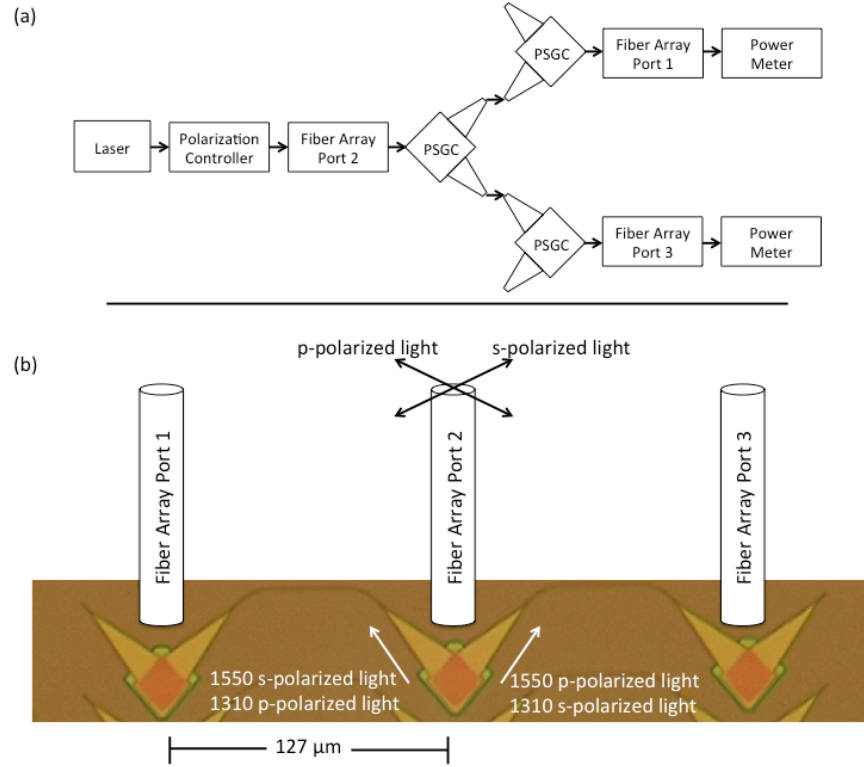


Fig. 6. (a) Schematic block diagram of test setup. (b) Optical micrograph of test cell to extract device performance with a schematic illustration of the test setup overlaid. Light is launched into the center grating coupler and the output is measured from the left and right couplers.

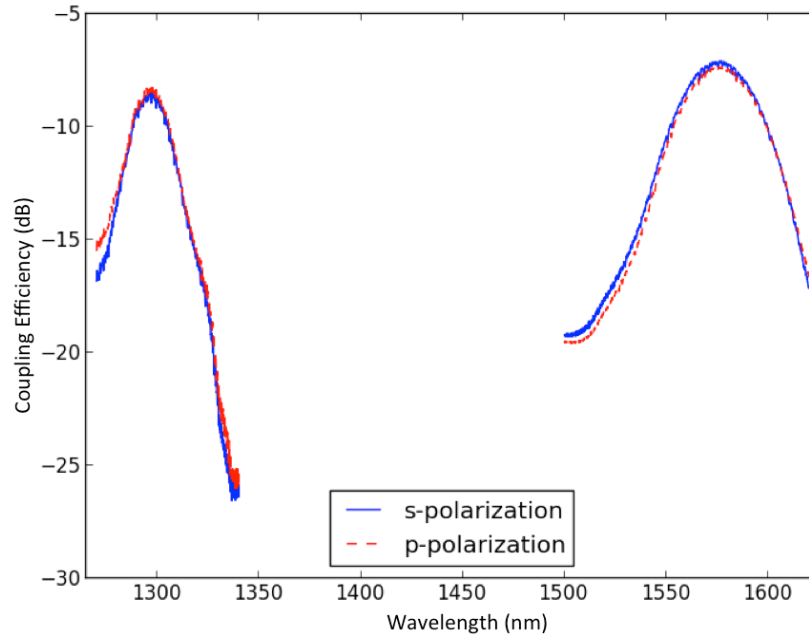


Fig. 7. Measured transmission spectrum of the device. Maximum transmission of -8.2 and -7.1 dB is observed for the wavelength bands near 1300 nm and 1550 nm, respectively.

Polarization dependent loss (PDL) measurements at 1550 nm are shown in Fig. 8. A similar test was performed at 1310 nm. PDL at 1550 nm is 1.06 dB, while PDL at 1310 nm is measured to be 5.6 dB. It is also possible to extract a lower bound for polarization isolation from PDL measurements. In the worst case, PDL is due entirely to interference between the desired polarization and undesired coupling from the opposite polarization. In this situation, the swing in total power will be the difference between the cases where the desired and undesired fields inside the output waveguide add constructively and destructively. Therefore, based on the PDL measurements, the minimum polarization isolation is found from the relationship:

$$PDL = 2 \cdot 20 \log_{10} \left(1 + 10^{\frac{P_{\text{isolation}}}{20}} \right) \quad (3)$$

With 1.06 dB PDL at 1550 nm, this corresponds to a polarization isolation of 24 dB. Similarly, polarization isolation at 1310 nm is calculated to be 8.4 dB. Since there may be other sources of PDL, this calculation understates the polarization isolation for linearly polarized light.

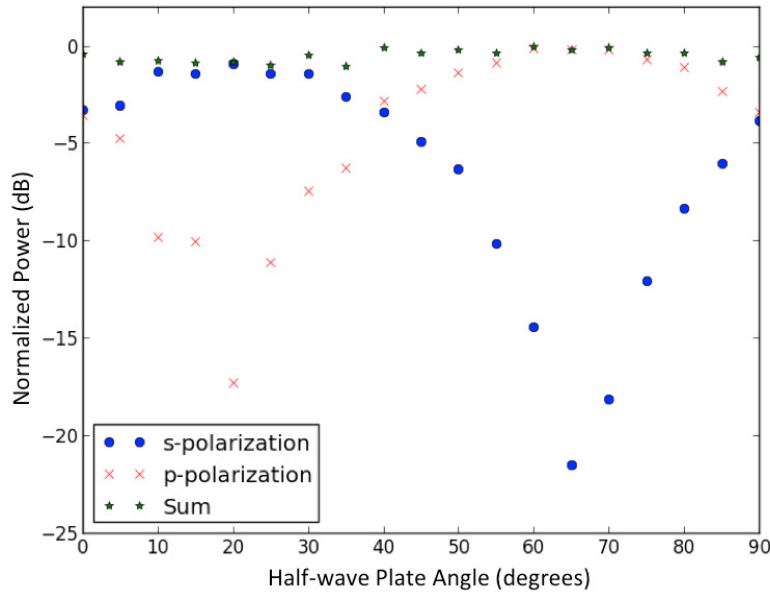


Fig. 8. Polarization dependent loss near 1550 nm is less than 1.06 dB.

There are several design parameters that may be changed in order to improve polarization isolation. The large tilt angle of approximately 20° is likely the root cause of PDL in this device [15]. By choosing wavelengths nearer to 1310 nm and 1550 nm, the optimum fiber angle would be closer to vertical. Introducing a π phase shifter in one of the output waveguides has also been shown to improve PDL [28]. Furthermore, as noted in [3], the shape of the scattering element also has a large impact on polarization dependence. Meklis et al. found that purely circular scatterers performed much worse than the rounded diamond-like pattern that is used in both of these works. It is likely that further experiments with the device

geometry are necessary in order to find a shape that effectively isolates in both wavelength bands.

There are also several design parameters that may improve coupling efficiency. FDTD simulations of our device predict that 59% of the power is lost due to coupling into the substrate at 1570 nm. This is significantly higher than the typical 35-45% substrate coupling in standard grating couplers [29]. Thus, to improve coupling efficiency, substrate coupling should be addressed first. Two solutions that have been demonstrated in literature to decrease this substrate coupling are a polysilicon overlay [13] and a backside metal mirror [14]. Additionally, a thicker top-silicon thickness substrate may be used to improve directionality of the gratings [9]. Finally, changing the lithographic exposure from 248 nm to 193 nm would enable much sharper features. In particular, smaller features would enable the coupling of light that is closer to 1550 nm and 1310 nm, rather than near 1570 nm and 1290 nm.

5. Conclusion

In this work we have experimentally demonstrated a compact polarization splitting grating coupler with two transmission windows near 1310 nm and 1550 nm using the same fiber angle. While losses are high compared to single wavelength PSGCs or bi-wavelength single polarization grating couplers, it is expected that with further optimization this type of device may prove useful for telecommunication systems such as FTTH PON networks. This is, to the authors' knowledge, the first experimental demonstration of a bi-wavelength PSGC.

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