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Three-dimensional long-period waveguide gratings for mode-division-multiplexing applications

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Abstract: We propose a three-dimensional (3D) long-period grating structure that has a controllable grating width and depth and can be formed at any chosen position on the surface of a waveguide core with a single photolithography process. The process relies on the partial etching of small structures on the surface of a polymer waveguide through a waveguide mask with narrow apertures that define the grating pattern. The 3D grating structure allows the design of mode converters for any nondegenerate guided modes of a waveguide, regardless of their symmetry properties, and thus relaxes the design constraint of conventional two-dimensional waveguide gratings. To show the flexibility of the 3D grating structure, we present several mode converters fabricated with this structure. The mode-conversion efficiencies achieved are higher than 90% at the resonance wavelengths. In addition, we demonstrate a three-mode multiplexer by integrating a grating-based mode converter with two asymmetric directional couplers. The proposed grating structure together with the fabrication process can greatly facilitate the development of grating-based devices, especially for MDM applications.

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References and links

1. **Introduction**

A long-period waveguide grating (LPWG), which is a periodic structure formed along an optical waveguide, can be designed to enable strong coupling from a guided core mode to a co-propagating cladding mode at a specific resonance wavelength [1, 2]. Such a cladding-mode LPWG has been explored as a basic structure for the realization of a wide range of wavelength-selective devices, which include band-rejection filters [3–6], bandpass filters [7], wavelength add-drop multiplexers [8], thermo-optic [9, 10] and electro-optic [11, 12] tunable filters, etc. In recent years, the LPWG structure has been applied to the construction of mode converters [13–16], where the grating is designed to enable coupling between the fundamental mode and a higher-order mode of a few-mode waveguide. Mode converters are important devices for the development of the mode-division-multiplexing (MDM) technology, where different spatial modes of a few-mode fiber carry different signal channels. As existing fiber devices are mostly single-mode devices, it is necessary to perform conversion between the fundamental mode and a high-order mode at the transmitting and receiving ends of an MDM system. More general mode conversion functions are needed in advanced reconfigurable MDM networks that involve routing and switching of modes. MDM is a promising technology to increase the transmission capacity of fiber communication systems [17, 18] and can also be applied to optical sensing systems to improve measurement accuracy and facilitate multi-parameter measurements [19]. While LPWGs are usually conceived as strongly wavelength-sensitive devices, ultra-broadband grating-based mode converters with bandwidths well over 100 nm have been demonstrated recently by using special grating profiles [16]. Such mode converters are suitable for application in MDM systems that transmit wavelength-division-multiplexed signals. In this paper, we propose a flexible grating structure to realize mode converters for MDM applications.

An LPWG can be formed by corrugating the surface or a sidewall of a waveguide with the conventional photolithography process. In the case of fabricating a surface grating,
photolithography is applied twice with two masks, one for the waveguide core and the other for the grating, while in the case of fabricating a sidewall grating, only a single photolithography process is required, as the mask already contains the grating pattern. A conventional LPWG is a two-dimensional (2D) structure, as the corrugations extend over the entire width (for a surface grating) or height (for a sidewall grating) of the waveguide core. Because of that, mode converters based on 2D gratings only work for modes with certain symmetry properties [14–16]. An approach to realizing more advanced mode-conversion functions is to cascade carefully matched surface and sidewall gratings [15], but the use of multiple gratings adds significant complexity to the design and the fabrication of the device, not to speak of increasing the total length and the propagation loss of the device. The design constraint of a 2D grating can be removed by using a three-dimensional (3D) grating, i.e., a grating with controlled width and depth, formed at any chosen position on the surface of a waveguide core. In principle, it should be possible to etch such a surface 3D grating by conventional photolithography, but the use of two waveguide masks makes it difficult to control the position of the grating to a sufficient accuracy.

In this paper, we propose a 3D grating structure that can be formed anywhere along the surface of a waveguide core with a single photolithography step. This process requires only one waveguide mask, which defines both the waveguide core and the grating, so that the position of the grating on the core can be specified precisely. We take advantage of the different etching rates for the core (defined by a large window in the mask) and the grating (defined by much smaller apertures in the mask) to achieve simultaneous formation of the core and the grating. Using polymer as the waveguide material, we demonstrate the flexibility of this process with several mode converters, which differ in the locations of the gratings on the core surface. Our fabricated mode converters show conversion efficiencies higher than 90% at the resonance wavelengths. In addition, by integrating this new type of mode converter with two asymmetric directional couplers, we demonstrate a grating-based three-mode multiplexer, which has mode-dependent losses lower than 2.8 dB. The proposed 3D grating structure together with the fabrication process can greatly facilitate the development of grating-based devices, especially for MDM applications.

2. Grating structure

To design a mode converter with a uniform LPWG, we need to determine the pitch, the length, and the corrugation depth of the grating [1,2]. The pitch of the grating \( \Lambda \) is given by

\[
\Lambda = \frac{\lambda_0}{(N_1 - N_2)},
\]

where \( \lambda_0 \) is the resonance wavelength at which the mode coupling effect is the strongest, and \( N_1 \) and \( N_2 \) are the effective indices of the two coupled modes, respectively. The mode-conversion efficiency is governed by the product \( \kappa L \), where \( \kappa \) is the coupling coefficient that measures the spatial overlap between the fields of the two coupled modes in the grating area and \( L \) is the grating length. 100% mode conversion occurs at the resonance wavelength when \( \kappa L = \pi/2 \). Whether conversion between a pair of modes is allowed depends on the spatial overlap of the fields of the two modes in the grating area (i.e., whether the value of \( \kappa \) is equal to zero or not) and, therefore, the symmetry properties of the modes [15].

To facilitate discussion, we consider a rectangular-core waveguide that supports 6 spatial modes, each of which consists of two almost degenerate orthogonal polarizations. For a rectangular-core waveguide, the spatial modes are designated as the \( E_{mn} \) modes, where \( m \) and \( n \) are the numbers of peaks in the electric-field distributions along the horizontal and vertical axes of the core, respectively. The 6 spatial modes supported by the waveguide are the \( E_{11} \), \( E_{12} \), \( E_{21} \), \( E_{13} \), \( E_{31} \), and \( E_{22} \) modes. A conventional surface grating, which have corrugations formed across the entire width of the core, permits conversion only between two modes that have the same symmetry with respect to the vertical axis of the core, such as \( E_{11} \rightarrow E_{12} \), \( E_{11} \rightarrow E_{13} \), \( E_{12} \rightarrow E_{13} \), and \( E_{21} \rightarrow E_{22} \) mode conversion. Similarly, a conventional sidewall grating, which have
corrugations formed across the entire height of the core, permits conversion only between the modes that have the same symmetry with respect to the horizontal axis of the core, such as $E_{11}-E_{21}$, $E_{11}-E_{31}$, $E_{21}-E_{31}$, and $E_{12}-E_{22}$ mode conversion. It is impossible to achieve $E_{11}-E_{22}$ and $E_{21}-E_{12}$ mode conversion with a conventional surface grating or sidewall grating, because the value of $\kappa$ for these mode pairs is zero. While $E_{13}-E_{31}$ mode conversion is in principle possible with a conventional grating, it is difficult to achieve a high conversion efficiency, because of their weak field overlap in the grating area.

To remove the design constraint of conventional 2D gratings, we propose a 3D grating structure, as shown in Fig. 1(a), which consists of a series of small dents on the surface of the core of a fully buried few-mode waveguide. As the position of the grating can be controlled to produce a significant field overlap between any two modes over the grating area, the proposed grating permits conversion between any two modes of the waveguide. Figure 1(b) shows the electric-field patterns of the 6 spatial modes of the waveguide, where the arrows indicate that conversion between any two modes of the waveguide can be achieved with the proposed grating. As this grating structure permits conversion between any two modes, it can be designed to function as a mode rotator that converts a vertically anti-symmetric mode into a horizontally anti-symmetric mode. With such a mode rotator, mode multiplexing can be achieved with planar waveguide structures instead of 3D waveguide structures [20–23]. The integrated three-mode multiplexer presented in Section 4.3 is a demonstration of such a planar waveguide structure.

Fig. 1. (a) Schematic diagram of the proposed 3D grating structure and (b) mode-conversion functions achievable with the grating structure for a waveguide that supports 6 spatial modes.

3. Fabrication process

Fig. 2. Steps for the fabrication of the proposed grating structure with polymer material.

The steps in the photolithography process developed for the fabrication of the proposed 3D grating structure with polymer material are illustrated in Fig. 2. First, a low-index polymer film is spin-coated on a silicon (Si) substrate to form a lower cladding. A high-index polymer film is next spin-coated on the lower cladding to form the core layer, which is then exposed to ultraviolet (UV) light through a chromium (Cr) waveguide mask that contains both the core pattern and the grating pattern. The grating pattern consists of narrow periodic metal strips at the
desired locations in the core area. The metal strip, which has a width typically 10% to 20% of the core width, casts a shadow on the core layer. As a result, the shadowed core area is underexposed, while the remaining core area is fully exposed. In the development process, the etching rate for the shadowed core area is much lower than that for the unexposed area. After development, the shadowed core area is only slightly etched, which leaves periodic dents on the surface of the core as a grating. Finally, an upper cladding of low-index polymer is spin-coated onto the core to complete the process. We should mention that a similar process has been applied to the fabrication of multilevel microfluidics devices [24].

Fig. 3. (a) Photos of three Cr masks (from top to bottom): a 2-μm strip placed at the center of the core, a 2-μm strip placed near one side of the core, and a 1.0-μm strip placed at the center of the core. (b) Cross sections of waveguides fabricated at an UV dose of 360 mJ/cm² using a mask without a Cr strip in the core area (left) and a mask with a 2-μm Cr strip in the core area (right).

Fig. 4. (a) Photos showing the dents produced at an UV dose of 360 mJ/cm as the width of the Cr strip in the core increases from 1.0 to 2.1 μm and (b) dependence of the cross-sectional area of the corrugation (i.e., the size of the dent) produced on the width of the Cr strip in the core measured at three different UV doses.

For the design of the 3D grating, we need to evaluate the coupling coefficient κ, which requires knowledge of how the corrugation depth of the grating depends on the mask and the fabrication parameters. In our study, the polymer materials EpoCore and EpoClad (Micro Resist Technology) (or their mix) were used as the core and the cladding material, respectively. As EpoCore is a negative tone photoresist, the intensity of the diffracted UV light through the mask depends on the width of the metal strip in the core, which thus allows us to control the corrugation depth by controlling the UV exposure time and the width of the metal strip on the mask. Figure 3(a) shows three typical Cr masks, which differ in the location and the width of the Cr strip in the core. Figure 3(b) shows the cross sections of two waveguides, one fabricated with a mask that does not contain a Cr strip in the core area and the other fabricated with a mask.
that contains a 2-μm Cr strip in the core area. The width and the height of the core are 12 and 10 μm, respectively, and the UV dosage used is 360 mJ/cm², which gives a corrugation area of about 1.5 μm². As shown in Fig. 3(b), a small dent is produced on the surface of the core through the mask that contains a Cr strip in the core area, which confirms the feasibility of the fabrication process. We carried out a series of experiments with a large number of masks to determine the dependence of the size of the dent produced by the process on the width of the Cr strip in the core area and the UV dosage. Figure 4(a) shows how the size of the dent produced increases, as the width of the Cr strip in the core area increases from 1.0 to 2.1 μm. Figure 4(b) summarizes the results for three UV doses, 240, 360, and 600 mJ/cm. With the results in Fig. 4(b), we can choose a proper width of the Cr strip in the core to optimize the coupling coefficient $\kappa$ for a given grating length $L$ and a given position of the grating.

We should note that the experimental results presented in Fig. 4 are specific to the polymer material used in our study. The process will need to be characterized for different material systems.

4. Examples of fabricated devices

In this section, we present several typical mode converters fabricated with the proposed 3D grating structure to demonstrate the flexibility of the grating structure.

4.1 $E_{11} - E_{12}$ mode converter

We first present an $E_{11} - E_{12}$ mode converter, where the grating is located along the central axis of the core to optimize the field overlap between the two modes, as shown in Fig. 5(a). The refractive indices of the core and the cladding of the waveguide are $n_{co} = 1.571$ and $n_{cl} = 1.564$, respectively, which are the values measured at 1536 nm with a prism coupler (Metricon 2010) for thin-film samples formed with the same polymer materials. The thickness of the lower cladding is ~25 μm and the thickness and the width of the core are $H = 11.6$ μm and $W = 12.5$ μm, respectively. We solve the modes of the waveguide with a commercial mode solver (COMSOL), from which we determine the pitch of the grating from Eq. (1) at 1550 nm and the corrugation depth and the length of the grating required for achieving 100% mode conversion [14]. The grating pitch is $\Lambda = 630$ μm. From the results in Fig. 4(b), we choose an UV dose of 360 mJ/cm² and a Cr-strip width of 2.0 μm. The grating consists of 15 periods, i.e., the length of the grating is $L = 9.45$ mm. The total length of the fabricated device is ~15 mm, which includes lead waveguide sections at both ends. Figure 5(b) shows microscopic images of the fabricated device, where the upper one is the cross-sectional view of the finished device and the lower one is the top view of the device taken before the upper cladding was applied.
Fig. 5. (a) Schematic diagram of the proposed $E_{11}$–$E_{12}$ mode converter, where the grating is placed along the central axis of the core; (b) cross-sectional (upper) and top views (lower) of the fabricated $E_{11}$–$E_{12}$ mode converter; (c) transmission spectra of the $E_{11}$ mode measured for the $E_{11}$–$E_{12}$ mode converter; and (d) output near-field images of the $E_{11}$–$E_{12}$ mode converter taken at different wavelengths with only the $E_{11}$ mode launched into the device.

To characterize the mode converter, we launched only the $E_{11}$ mode into the device with a lensed fiber and a broadband source (SuperK COMPACT, KOHERAS) and measured the transmission spectrum of the $E_{11}$ mode at the output end with another lensed fiber and an optical spectrum analyzer (AQ6370, Yokogawa). The polarization of light was controlled with a polarization controller and a polarizer placed at the input and output ends, respectively. The transmission spectra measured for the $x$- and $y$-polarizations are shown in Fig. 5(c). As shown in Fig. 5(c), the transmission characteristics of the grating are insensitive to the polarization state of light and the maximum contrast is about $-18$ dB at $1545$ nm, which corresponds to a mode-conversion efficiency of $\sim98\%$ (assuming that all the power lost from the $E_{11}$ mode went to the $E_{12}$ mode). Figure 5(d) shows the output near-field images taken at different wavelengths for the two polarizations when the $E_{11}$ mode was launched into the device. These images confirm that the $E_{11}$ mode is converted into the $E_{12}$ mode. We measured the propagation loss of a reference waveguide with the same core dimensions by the cutback method at $1550$ nm. The loss is about $2.3$ dB/cm. By comparing the losses of the reference waveguide and the mode converter, we find that the grating-induced loss is less than $0.5$ dB, which confirms that almost all the power lost from the $E_{11}$ mode goes to the $E_{12}$ mode.

4.2 $E_{11}$–$E_{22}$ mode converter

We next present an $E_{11}$–$E_{22}$ mode converter, where the grating is placed off the central axis of the core, as shown in Fig. 6(a). The refractive indices of the materials and the dimensions of the core are all the same as those for the $E_{11}$–$E_{12}$ mode converter given in the previous section. The grating is located $2.0$ µm away from the central axis of the core. Again, the UV dose used is $360$ mJ/cm² and the width of the Cr strip is $2.0$ µm. For this grating, the pitch is $\Lambda = 370$ µm.
and the length is $L = 18.9$ mm (51 periods). The total length of the fabricated device is ~25 mm. Figure 6(b) shows microscopic images of the fabricated device, where the upper one is the cross-sectional view of the finished device and the lower one is the top view of the device taken before the upper cladding was applied.

The transmission spectra of the device measured for the $x$- and $y$-polarizations are shown in Fig. 6(c). The maximum contrast is about $-13$ dB at ~1575 nm, which corresponds to a mode-conversion efficiency of 95%. Like the $E_{11}$–$E_{12}$ mode converter, the performance of this mode converter is insensitive to the polarization state of light. Figure 6(d) shows the output near-field images of the mode converter taken at different wavelengths with only the $E_{11}$ mode launched into the device. These results confirm the operation of the device as an effective $E_{11}$–$E_{22}$ mode converter. The propagation loss and the grating-induced loss are similar to those for the $E_{11}$–$E_{12}$ mode converter.

4.3 Three-mode multiplexer based on an $E_{21}$–$E_{12}$ mode converter

An $E_{21}$–$E_{12}$ mode converter is a mode rotator, which can be used for the realization of mode multiplexers [25, 26]. A mode rotator has been implemented with a waveguide that contains a precisely etched trench in the core [25, 26] or by cascading a surface grating and a sidewall grating [15]. Our 3D grating structure provides a simpler approach to the implementation of an $E_{21}$–$E_{12}$ mode converter, as its fabrication requires only a single photolithography process, as described in Section 3.
Figure 7(a) shows a schematic diagram of our proposed E$_{21}$-E$_{12}$ mode converter, where the grating is placed off the central axis on the core. Instead of demonstrating an E$_{21}$-E$_{12}$ mode converter alone, we present a three-mode multiplexer by integrating an E$_{21}$-E$_{12}$ mode converter with two identical asymmetric directional couplers. The layout of the multiplexer is shown in Fig. 7(b). With reference to Fig. 7(b), the E$_{11}$ mode launched into Core 2 is coupled to the E$_{21}$ mode in Core 1 by the directional coupler DC1. The E$_{21}$ mode in Core 1 is then converted into the E$_{12}$ mode through the E$_{21}$-E$_{12}$ mode converter and exits from Core 1 as the E$_{12}$ mode. The E$_{11}$ mode launched into Core 1 is not affected by the directional couplers and exits directly from Core 1. The E$_{11}$ mode launched into Core 3 is coupled to the E$_{21}$ mode in Core 1 by the directional coupler DC2 and exits from Core 1 as the E$_{21}$ mode. In this way, the three E$_{11}$ modes launched separately into the three cores at the demultiplexing end are combined into three different modes at the multiplexing end. Two tapers, Taper 1 and Taper 2, are incorporated along Core 1 to improve the performance of the device. Taper 1 serves to filter out all higher modes, while Taper 2 serves to shape Core 1 for better alignment with a few-mode fiber. The reason of using a mode rotator is that a planar directional coupler does not permit coupling between the E$_{11}$ mode and the E$_{12}$ mode. While 3D directional couplers have been demonstrated for effective coupling between the E$_{11}$ mode and the E$_{12}$ mode [21–23], their fabrication requires two waveguide masks and careful alignment of structures in different layers. On the other hand, the present multiplexer can be fabricated with a single mask and a much simpler process.

We fabricated the mode multiplexer with the polymer materials EpoCore and EpoClad by following the process described in Section 3. The refractive indices of the core and the cladding are 1.571 and 1.561, respectively. The use of a somewhat larger core-cladding index difference
for this device (compared with that used for the devices discussed earlier) allows a more compact design. The height of all the cores is $H = 6.3 \, \mu m$ and the widths of Core 2 and Core 3 are 5.0 \, \mu m. The width of Core 1 changes from 5.0 to 13.2 \, \mu m through Taper 1 and then decreases to 8.0 \, \mu m through Taper 2. The two directional couplers have identical dimensions and, therefore, the same coupling length, which is 2.5 \, mm. The grating pitch is $\Lambda = 420 \, \mu m$ and the grating length is 7.56 \, mm (18 periods). The total length of the device is 30 \, mm. The length of each taper is 2.0 \, mm. The Cr strips on the waveguide mask are located at 2.0 \, \mu m away from the center of the core and the Cr-strip width used is 2.0 \, \mu m. The UV dosage used is 360 mJ/cm$^2$, which should give a corrugation area of 1.5 \, \mu m$^2$ required for achieving maximum mode conversion. Figure 7(c) shows a microscopic image of a top view of the fabricated device taken before applying the upper cladding, where we can see a strip of partially etched structure on Core 1 with a length of 210 \, \mu m (half of the grating pitch). Figure 7(d) shows microscopic images of the two end faces of the device.

To demonstrate the operation of the device, we launched light into the three cores individually from the demultiplexing end with a tunable laser (KEYSIGHT) through a lensed fiber and took images of the corresponding outputs at the multiplexing end of the device with an infrared camera. The results are shown in Fig. 8(a), which confirm that the $E_{11}$ modes launched into Core 1, Core 2, and Core 3 from the demultiplexing end exit as the $E_{11}$, $E_{21}$, and $E_{11}$ modes, respectively, from Core 1 at the multiplexing end. We also measured the output powers from the three cores with a power meter. Figure 8(b) shows the ratios of the output powers from Core 1 over the total output power from the three cores, when laser light was launched into the three cores individually from the demultiplexing end. These power ratios can be understood as the coupling ratios from the three cores to Core 1. As shown in Fig. 8(b), the coupling ratio from Core 3 to Core 1 is higher than 95% in the C band, which is governed by the performance of DC2, while the coupling ratio from Core 2 to Core 1 is higher than 80% in the C band, which is governed by the combined performance of DC1 and the mode converter. The coupling ratios show weak polarization dependence. At 1550 nm, the coupling ratio from Core 3 to Core 1 is 98% (which is also the coupling ratio of DC2) and the coupling ratio from Core 2 to Core 1 is 92%. Assuming that DC1 also has a coupling ratio of 98% at 1550 nm, we deduce that the mode converter has a conversion efficiency of 92/98 $\approx$ 94% at 1550 nm. Compared with the coupling ratio from Core 3 to Core 1, the coupling ratio from Core 2 to Core 1 has a narrower bandwidth, which is due to the narrower bandwidth of the grating.

We measured the insertion losses and the mode-dependent losses of the multiplexer by launching laser light at 1550 nm into the three cores individually from the demultiplexing end with a single-mode fiber and comparing the corresponding output powers from Core 1 with the input powers. The insertion losses for the $E_{11}$ mode (Core 1 to Core 1), the $E_{21}$ mode (Core 2 to Core 1), and the $E_{12}$ mode (Core 3 to Core 1) were obtained as 9.3, 10.3, and 12.1 dB, respectively, which include the fiber-waveguide coupling loss (~2 dB) at the input end. The mode-dependent loss of the device is 2.8 dB. Any incomplete mode couplings with the directional couplers lead to reduced output powers from Core 1 and hence contribute to the insertion losses for the $E_{21}$ and the $E_{12}$ modes. The propagation losses of the waveguides, as measured with reference waveguides, are in the range of 2.5 – 3.5 dB/cm for the three modes. The large propagation losses are mainly due to the material, which is developed for application at 850 nm and has a loss of about 2 dB/cm at 1550 nm. It should be possible to substantially reduce the insertion losses of the device by using low-loss polymer material developed for the C band [27] and further optimizing the fabrication parameters. As the directional couplers are highly mode-selective and Taper 1 can effectively strip off all high-order modes, the crosstalks among the three modes are negligible ($< -20$ dB).
5. Conclusion

We have proposed a 3D LPWG structure that can be formed anywhere on the surface of a waveguide with a single mask by photolithography. This grating structure relaxes the symmetry constraints of conventional 2D LPWG structures in the design of mode converters, which are important devices for the development of the MDM technology. To demonstrate the feasibility and the flexibility of the proposed grating structure and the fabrication process, we present three mode converters fabricated with polymer material: an E11–E12, an E11–E22, and an E12–E21 mode converter, where the E12–E21 mode converter is integrated with two asymmetric directional couplers to form a three-mode multiplexer. The performance of these devices is polarization-insensitive and the mode-conversion efficiencies at the resonance wavelengths are higher than 90%. The proposed 3D LPWG structure together with the fabrication process greatly expands the range of devices that can be formed with waveguide gratings, especially for MDM applications. Previously reported techniques for increasing the bandwidths of LPWGs, such as length-apodization [16] and cladding-profile control [28], are applicable to the proposed 3D LPWG structure.

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