produced, or the same thresholds for both modes can be obtained, which results in the third state.

By using the tuning scheme to apply axial and lateral strain on the FBG, we can change the wavelengths of the dual-wavelength laser. Figure 3 shows the output spectrum of the EDFL when the axial strain is 818 με (according to the translation stage’s displacement of 0.1 mm) and the screw angle is 50°. The dual lasing wavelengths are 1554.44 and 1554.84 nm, respectively.

Figure 4 shows the dependence of the wavelength spacing upon the lateral strain when the axial strain is zero and Figure 5 shows the wavelength shift with respect to the axial strain when the lateral strain is zero. Linear responses were observed in both figures. Considering the mechanical properties of glass fiber, the wavelength shift cannot exceed ~2 nm using the axial-strain tuning method.

4. CONCLUSION
In conclusion, we have demonstrated a tunable, stable dual-wavelength EDFL at room temperature with only a single-mode FBG applied with lateral strain. Adjusting a PC in the cavity allows us to achieve either single- or dual-wavelength laser outputs. Two lasing wavelengths of this simple and low-cost laser can be tuned continuously.

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REFERENCES

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DESIGN AND ANALYSES OF COMPACT BENT-TAPERED WAVEGUIDES USING GUIDED-WAVE LENS SETS
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ABSTRACT: We propose compact bent-tapered waveguides using guided-wave lens sets, which are constructed by disposing lens-shaped waveguide regions in planar tapered waveguides. Two applications of the abruptly bent tapered waveguide and the Z-bend tapered waveguide demonstrate high transmittances of 91% and 86% with bent and tapered waveguides.
1. INTRODUCTION

Low-index-contrast silica waveguides, offering low propagation losses and high-efficiency coupling with a single-mode fiber, have been utilized in a number of opto-electronic communication devices. In such devices, waveguide tapers and waveguide bends are frequently used to interconnect integrated photonic devices with different cross sections and directions. However, the tapered angles and the bent angles should be less than 2° to prevent serious radiation losses in the low-index-contrast waveguides [1]. These limitations are obstacles to realizing high-density photonic integrated circuits (PICs), and thus prevent the production cost from being reduced. Hence, shorter bent-tapered waveguides, which combine the functions of waveguide bends and tapers, are desired.

Much attention has been paid to the design and analyses of waveguide tapers [2, 3] and waveguide bends [4–6]. Marcadali [7] presented a design procedure, based on the scalar wave equation, for developing lossless curved-axes tapered waveguides. Although these ideal waveguide structures cannot be readily implemented in practical applications, they do provide good insight into the mechanism of the operation of curved-axis waveguides. Using the guided-wave lenses [8], we have analogized guided-wave telescopes in order to design planar tapered waveguides [3], in which an input mode can only be converted along a straight axis. In this paper, we extend the application of guided-wave telescopes to bent-tapered waveguides by introducing lateral displacements between the axes of the optical elements in the guided-wave telescope structures. The function of the laterally shifted lens sets can be regarded as being equivalent to that of a combination of planar prisms and mode converters.

The methods of designing the proposed bent-tapered waveguides are based on a combination of the paraxial transfer-function method (TFM) and ray optics with guided-wave parameters. Two bent-tapered waveguides, the abrupt-bent tapered (ABT) waveguide and the Z-bend tapered (ZBT) waveguide, are demonstrated to elucidate the functions of the proposed schemes. This investigation applies the beam-propagation method (BPM) to calculate the transmission efficiency of the proposed bent-tapered waveguides. Meanwhile, reflection and scattering from the boundaries of waveguide lenses are investigated using the finite-difference time-domain (FDTD) method. The transmission spectra of the bent-tapered devices are discussed to verify the applicability of the proposed devices in wide-bandwidth optical-fiber communication systems.

2. THEORY

Figure 1(a) depicts a tapered waveguide with a guided-wave telescope structure [3]. Lens A with a positive focal length \( f_a \) and lens B with a negative focal length \( f_b \) are employed to transform a broad plane-wave beam into a narrower beam, such that the Galilean condition, \( \Delta z = f_a - |f_b| \), is fulfilled, where \( \Delta z \) is the tapered length. Figure 1(b) presents the proposed ABT waveguide. The guided-wave lens set in the ABT waveguide is the same as that shown in Figure 1(a), but with a lateral shift between the two lenses. Introducing the lateral shift between the guided-wave lenses bends the waveguide beam to the output channel of the ABT with an angle \( \theta \), which can be predicted from the paraxial TFM. The paraxial transfer function of these two lenses in Figure 1(b), using the thin-lens approximation, can be expressed as

\[
U(x, z = z_b^*) = E(x) \exp\left( -\frac{\pi x^2}{\lambda f_a} \right),
\]

where \( E(x) \) represents the initial distribution of the electric field of the beam. It is a spherical wave that converges to the focus of lens A. After the beam has traveled a distance of \( \Delta z \) to reach lens B, the beam diameter is reduced and the radii of the curvatures of the wavefronts exactly match the curvature of lens B. Immediately, behind lens B, the amplitude \( \tilde{U} \) of the propagating wave is given by

\[
\tilde{U}(x, z = z_b) = E(x) \frac{f_a}{f_b} \exp\left( -\frac{\pi x^2}{\lambda f_a} \right) \exp\left( -\frac{2\pi \Delta k \Delta x}{\lambda f_b} \right).
\]

The first phase term of Eq. (3) is a constant, whereas the second term represents a linear phase shift across the aperture of the lens and is proportional to the lateral shift \( \Delta x \). Consequently, the complex amplitude specified by Eq. (3) reveals that the laterally...
shifted telescope structure not only serves as a plane-wave beam-shaping system, but also as a refractive prism that deflects the incoming plane-wave beam to an angle, given by

$$\theta_t = -\arctan \left( \frac{\Delta x}{f_o} \right). \quad (4)$$

The negative sign indicates that the deflection takes place in the direction opposite to the lateral shift.

Similarly, the parameters used to design the ZBT waveguides can also be obtained using the TFM. The ZBT waveguide is composed of a truncated telescope and a bent-tapered waveguide, as shown in Figure 1(c), where $O_t$ and $O_{oc}$, which are separated by $\Delta x$, are axes of the guided-wave telescope and the input waveguide, respectively. Consider a plane-wave beam incident onto lens $A$ with a focal length $f_A$; the transmitted amplitude of the collimated beam immediately after lens $A$ is given by

$$\bar{U}(x,z) = E(x) \exp \left( -\frac{\pi \Delta x^2}{f_A} \right) \exp \left( -\frac{\pi x^2}{f_A} \right) \exp \left( \frac{2\pi \Delta x}{f_A} \right). \quad (5)$$

The second phase term of Eq. (5) specifies that the transmitted waves converge to the focus of lens $A$ in Figure 1(c). The third exponential term shows that the converging beam is deflected through the following angle:

$$\theta_t = \arctan \left( \frac{\Delta x}{f_o} \right). \quad (6)$$

Following multiplication by the transfer function of lens $B$, the outgoing beam is converted into a planar beam and then becomes parallel to the input channel.

3. DESIGN AND CALCULATIONS

3.1. Abrupt-Bent Tapered Waveguides

The core and cladding of the ABT waveguide with a bent angle of $\theta_b$, as shown in Figure 1(b), have refractive indices $n_c = 1.504$ and $n_s = 1.5$, respectively. In Figure 1(b), the straight waveguide with width $w_l = 27 \mu m$ is excited by the fundamental transverse electric (TE) mode of wavelength $\lambda = 1.5 \mu m$ and serves as the input channel of the tapered waveguide. Accordingly, the propagation constant $\beta$ and the effective waveguide width $w_{eff}$ of the input waveguide can be determined. The input waveguide is connected to the output waveguide via a tapered region with a tapered angle $\theta_t$. In these analyses, the width of the output waveguide is assumed to be $9 \mu m$; a tapered angle of $\theta_t = 10^\circ$ and bent angles of $\theta_b = 0 - 10^\circ$ are used. The focal length $f_{oc}$ of lens $A$ is given by

$$\sin(\theta_b) = \frac{w_{eff}/2}{\sqrt{(w_{eff}/2)^2 + f_{oc}^2}}, \quad (7)$$

when the tapered angle $\theta_t$ and the effective waveguide width $w_{eff}$ are specified. The radii of the curvatures of the lens set, $r_1$ and $r_2$, can be calculated using Lensmaker’s formula:

$$\frac{n_m}{T} = (n_i - n_m) \left( \frac{1}{r_1} - \frac{1}{r_2} \right), \quad (8)$$

where $f$ is the focal length of the lens, and $n_i$ and $n_m$ are the refractive indices of the lens and the ambient media, respectively. In this study, the guided-wave parameters, which are the effective refractive indices of the straight waveguides $n_{eff}$, are taken to be $n_{eff}$ and the refractive indices of the lenses are assumed to be $n_i = 1.5$ (Si$_3$N$_4$).

The grid size in the BPM calculation is 1/20 of the wavelength, and transparent boundary conditions are imposed to prevent reflection of the radiation waves at the boundaries of the calculation domain. The transmittance $\eta$ is determined from the overlap integral between the field calculated at the output position and the mode field of the output channel. Figure 2 shows the transmittance versus the bent angles of the ABT with $\theta_b = 10^\circ$. As indicated, the excess losses are less than 0.46 dB ($\eta = 91\%$) when the bent and tapered angles are both $10^\circ$. In Figure 3(a), the field distribution along the ABT waveguide with $\theta_b = 10^\circ$ shows that the propagating waves were tapered and bent with low radiation losses, performing low-loss mode conversions and high-efficiency transmission in the bent-tapered structure. Therefore, the guided-wave lens sets can considerably reduce the dimensions and the excess losses of the ABT waveguides when the bent angles are from 0° to 10°.

3.2. Z-bend Tapered Waveguides

In Figure 1(c), the ZBT waveguide constructed using the truncated guided-wave lens set provides a lateral offset in the waveguide path in order to enable the connection of two parallel noncollinear photonic devices with different cross sections. The parameters of the input and the output straight waveguides are the same as those of the ABT waveguide analyzed above. The truncated lens $A$, which has a focal length $f_A = 159.5 \mu m$, is separated from the truncated lens $B$ by a distance $\Delta x = 100.7 \mu m$. The aperture width of the truncated guided-wave lens sets should be sufficiently wide to cover the effective waveguide width of the input and output channels.

Figure 4 shows the transmittance of the ZBT waveguide against the bent angles. The excess losses are 0.65 dB ($\eta = 86\%$) when the bent angle is as large as 10°. Figure 5(a) plots the field intensity distribution of the ZBT waveguide with a bent angle of $\theta_b = 10^\circ$. The propagating waves in the input straight waveguide are tapered.
and bent properly by the lens sets. Therefore, the proposed ZBT waveguides providing low-loss bends and tapers of the propagating waves are appropriate for realizing the compact transverse offsets and cross section tapers in PICs.

3.3. Reflections and Scattering from the Waveguide-lens Boundaries

Since the waveguide lenses are made of material with higher indices ($\text{Si}_3\text{N}_4, n = 2.0$), reflection and scattering should occur at the waveguide-lens boundaries. However, the single-directional BPM is not suitable for investigating reflections. This study employs the FDTD method, which directly integrates Maxwell’s equations with respect to time in order to calculate the transmittance and reflectance, as presented in Figures 2 and 4 for the ABT and ZBT waveguides, respectively. From Figures 2 and 4, the excess losses caused by reflection and scattering from the lens boundaries are between 0.17 dB and 0.4 dB, which depend on the bent angles and the structures of the tapered waveguides. The respective electric-field distributions of the ABT and the ZBT waveguides shown in Figures 3(b) and 5(b) reveal that the cross sections of the guided modes were effectively converted due to the curved-wavefront effect caused by the waveguide lenses. The introduced lateral shifts yielded highly efficient bends and tapers. Furthermore, most of the reflected waves radiated out of the waveguide region and did not propagate backward along the input waveguide since the curved boundaries caused them either to diverge or to converge. The reflectances calculated by the FDTD method are both less than $-40\text{ dB}$ for the ABT and ZBT waveguides, which meet the requirements of digital-communication systems.

3.4. Wavelength Responses

The spectral responses of the proposed bent-tapered waveguides were analyzed as plotted in Figure 6 to verify the applicability of the proposed devices in optical-fiber communication systems. In spite of the dispersion of the guided-wave parameters used in the design, the transmittances of the proposed devices with tapered and bent angles of $10^\circ$ are uniform across the spectral range of 1400 to 1600 nm. The uniformity, which was defined as the maximum power divided by the minimum power, was 0.026 dB for the ABT waveguide and 0.058 dB for the ZBT waveguide, respectively. Accordingly, the proposed bent-tapered waveguides with uniform spectral responses are very useful in wide-bandwidth optical-fiber communication applications.

4. CONCLUSION

We have demonstrated two types of bent-tapered waveguides with low excess losses and wide bandwidths using guided-wave lens...
sets. The procedures for designing the proposed bent-tapered waveguides are derived from the paraxial TFM and ray optics with guided-wave parameters. The results of the BPM calculation reveal that the excess losses of the ABT and ZBT waveguides are less than 0.46 and 0.65 dB, respectively, when the bent and tapered angles are 10°. Consequently, the proposed method is very appropriate for designing high-packing-density PICs in wide-bandwidth optical-fiber communication systems.

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REFERENCES

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