3 \times 3 slot waveguide crossing based on Maxwell’s fisheye lens

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Abstract. Intersection of two or more silicon slot waveguides is inevitable in modern optical integrated circuits based on a silicon-on-insulator platform. We design a Maxwell’s fisheye lens as the crossing medium for three Si slot waveguides and numerically investigate its characteristics, such as insertion loss, cross talk, and bandwidth. For the 3 × 3 slot waveguide crossing, the average insertion loss of 1.2 dB and cross talk levels lower than −15.1 dB are achieved in an ultrawideband wavelength range of 415 nm covering the entire O, E, S, C, L, and U bands of optical communications. The footprint of the 3 × 3 silicon slot waveguide crossing presented in our paper is merely 2 × 2 μm², which is considerably smaller compared to the previously designed Si slot waveguide crossings even with fewer ports. The proposed design can be expanded to support the intersection of more slot waveguides. © 2019 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.58.9.097102]

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1 Introduction

As the number of components on the limited space of a modern optical integrated circuit increases, crossing of waveguides becomes inevitable, which makes compact waveguide crossings indispensable components for highly dense optical and photonic integrated circuits. Therefore, various methods have been proposed in the literature to efficiently cross Si rectangular[25] and phononic crystal[26,27] waveguides. Si slot waveguides are key building blocks for a silicon-on-insulator (SOI) platform due to their superior characteristics, such as high light confinement and low loss. Due to these features, many devices are presented based on Si slot waveguides, such as modulators,[11,12] sensors,[13,14] light sources,[15,16] demultiplexers,[17] polarization splitters,[18] all-optical logic gates,[19] quantum optical circuits,[20] and ring resonators.[21] However, only a few designs have been presented for the crossing of Si slot waveguides. In Ref. 22, slot-to-strip mode converters followed by a multimode interference device are utilized to cross two slot waveguides resulting in an average insertion loss of ~0.1 dB and cross talk levels of lower than −27 dB for a bandwidth of 200 nm. However, the footprint of the proposed device is considerably large, equal to 15.6 × 15.6 μm². The same method with logarithmical mode converters is also studied. In a bandwidth of 200 nm, the average insertion loss is about 0.2 dB and the cross talk is lower than −33 dB. Nevertheless, the footprint of 20.8 × 20.8 μm² is the drawback of the proposed device again, which makes it incompatible for highly dense integrated circuits. The transmission efficiency can also be improved by filling up the crossing slots locally with an insertion loss of ~1.1 dB. Vertical coupling is another method presented to reduce the radiation loss in the crossing of Si slot waveguides; however, the large footprint of 13.8 × 0.43 μm² makes it unsuitable for compact photonic integrated circuits. It is worth noting that all the above methods only support the crossing of two waveguides with the crossing angle of 90 deg.

In this paper, we design an intersection of three Si slot waveguides based on the imaging properties of the Maxwell’s fisheye (MFE) lens. Radiation of the point source on the surface of the lens is focused on the diametrically opposite point of the MFE lens. To the best of our knowledge, it is the first time that a 3 × 3 Si slot waveguide crossing is designed and numerically investigated. Moreover, the proposed method can be easily expanded to increase the number of intersecting waveguides by increasing the radius of the lens. The refractive index of the MFE lens is

\[ n_{\text{lens}}(r) = \frac{2 \times n_{\text{edge}}}{1 + (r/R_{\text{lens}})^2}, \quad (0 \leq r \leq R_{\text{lens}}), \tag{1} \]

where \( R_{\text{lens}} \) is the radius of the lens, \( r \) is the radial distance from the center of the lens, and \( n_{\text{edge}} \) is the refractive index of the lens at its edge. Recently, interesting applications have been introduced for gradient index lenses, such as MFE, Luneburg, and Eaton lenses.

2 Simple Intersection of Three Slot Waveguides

In this paper, an Si slot waveguide with slot width and height of \( w_s = 100 \text{ nm} \) and \( h = 250 \text{ nm} \), respectively, is considered. The width of the Si rails is \( w_h = 200 \text{ nm} \). Figure 1 illustrates the contour plot of the quasi-TE mode at \( \lambda = 1550 \text{ nm} \) for the slot waveguide where silicon rails are surrounded by silica. \( E_1 \) is the main electric field component, which is symmetric about the y axis and has a large discontinuity resulting in highly enhanced field in the slot. The guided mode displayed in Fig. 1 is confined in the slot by total internal reflection and consequently there are no confinement losses. The electric field distribution for a simple intersection of three slot waveguides at 1550 nm is shown in

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Fig. 2. Transmission, cross talk, and reflection values are also displayed in this figure. The diffraction at the simple intersection of three slot waveguides at 1550 nm. The electric field distribution for a simple intersection of three slot waveguides at 1550 nm.

Fig. 1 The contour plot of the quasi-TE mode at \( \lambda = 1550 \) nm for the slot waveguide. The silicon rails are surrounded by silica.

### 3 Multilayered Maxwell’s Fisheye Lens Design

When the width of the layers in the multilayer structure is comparable to the wavelength of the incident light, the interference is the dominant phenomenon in determining the response of the structure. Various devices have been designed based on the interference effect in multilayer structures.\(^6\)\(^3\)\(^5\)\(^6\)\(^7\)\(^8\)\(^9\) However, when the width of each layer is much smaller than the wavelength, the interference effect becomes negligible and the multilayer structure can be treated as an anisotropic metamaterial medium governed by effective medium theory.\(^6\)\(^3\)\(^5\)\(^6\)\(^7\)\(^8\)\(^9\)\(^10\)\(^11\)\(^12\)\(^13\)\(^14\)\(^15\)\(^16\)\(^17\)\(^18\)\(^19\)\(^20\)\(^21\)\(^22\)\(^23\)\(^24\)\(^25\)\(^26\)\(^27\)\(^28\)\(^29\)\(^30\)\(^31\)\(^32\)\(^33\)\(^34\)\(^35\)\(^36\)\(^37\)\(^38\)\(^39\)\(^40\)\(^41\)\(^42\)\(^43\)\(^44\)\(^45\)\(^46\)\(^47\)\(^48\)\(^49\)\(^50\)\(^51\)\(^52\)\(^53\)\(^54\)\(^55\)\(^56\)\(^57\)\(^58\)\(^59\)\(^60\) We implement the MFE lens based on this concept. Due to the symmetry of the refractive index profile of the MFE lens, it can be realized by a concentric-ring multilayer structure.\(^6\)\(^3\)\(^5\)\(^6\)\(^7\)\(^8\)\(^9\) Here, silicon and silica are considered as the constituting materials of the concentric-ring multilayer structure at which Si (SiO\(_2\)) serves as the host (incursion) material. The two components of the permittivity tensor, \( \varepsilon \parallel \) and \( \varepsilon \perp \), depend on the parallel or perpendicular arrangement of the inclusion layers with respect to the direction of the electric field and consequently have different values. In practice, the electric field is not purely TE or TM mode; therefore, the effective permittivity depends on both of these components. We simplify the design procedure by only considering \( \varepsilon \perp \) component\(^41\) where the inclusion layers are perpendicular to the electric field\(^12\)

\[
\varepsilon_{\text{eff}}^\text{TE} = \frac{\varepsilon_{\text{host}} - \varepsilon_{\text{inc}}}{1 - f_{\text{inc}}}.
\]

where \( \varepsilon_{\text{eff}}^\text{TE} \) is the effective permittivity of the cell for TE mode and \( \varepsilon_{\text{host}} \) and \( \varepsilon_{\text{inc}} \) are the permittivities of the host and inclusion materials, respectively. The filling factor, \( f_{\text{inc}} \), is the fraction of the total volume occupied by the inclusion layer. In our design, the lens is divided into equal segments with a width of \( \Lambda \). Afterward, the average refractive index in each layer (\( \varepsilon_{\text{eff}}^\text{TE} \)) is calculated. Subsequently, the width of the inclusion layer in the \( i \)th layer (\( d_i \)) is calculated. To do so, Eq. (2) is rearranged to give the filling factor for the effective permittivity as

\[
f_{\text{inc}} = \frac{\varepsilon_{\text{host}} - \varepsilon_{\text{inc}}}{\varepsilon_{\text{eff}}^\text{TE} - \varepsilon_{\text{host}}}.
\]

The filling factor for the \( i \)th layer is \( f_{\text{inc},i} = A_{\text{inc},i}/A_i \), where \( A_{\text{inc},i} = 2\pi r_id_i \) and \( A_i = 2\pi r_i\Lambda \) are the areas of the inclusion (in the \( i \)th layer) and the \( i \)th layer itself, respectively. Here, \( r_i \) is the distance from the origin to the middle of the \( i \)th layer. Therefore, \( d_i \) can be obtained by

\[
d_i = \frac{\varepsilon_{\text{host}}(\varepsilon_{\text{inc}} - \varepsilon_{\text{eff}}^\text{TE})}{\varepsilon_{\text{eff}}^\text{TE}(\varepsilon_{\text{inc}} - \varepsilon_{\text{host}})}\Lambda.
\]
structure, however, other methods such as varying the thickness of guiding layer and GPC can also be utilized to realize GRIN lenses.

4 Results and Discussion

In this paper, a two-dimensional finite-difference time-domain (FDTD) is utilized to evaluate the performance of the proposed Si slot waveguide crossing. Such a modeling procedure is proven to be accurate for similar structures previously.22,23,44 The built-in material models of silicon and silica of the Lumerical software are used in the simulations. A mode source is used to inject a TE mode into the simulation region where the maximum meshing step is 5 nm. The electric field distribution of the $3 \times 3$ slot waveguide crossing is shown in Fig. 4 at a wavelength of $\lambda = 1550$ nm. At this wavelength, the insertion loss is reduced from 11.2 (for the case of simple $3 \times 3$ crossing) to 1.1 dB by the help of the MFE lens. Cross talk to other ports is also reduced from $-4.7$ to $-16.0$ dB. The designed crossing has a small footprint of $2 \times 2 \mu m^2$. To compare the imaging quality of the designed MFE lens, the electric field intensity profiles at the input and output of the lens are compared in Fig. 5.

The scattering parameters of the $3 \times 3$ slot waveguide crossing are illustrated in Fig. 6. Since the electric field is confined in a subwavelength region in the slot waveguide, satisfying the effective medium condition requires the period of the structure to be smaller than the width of the slot. Hence, the period of the structure is chosen to be $\Lambda = 77.5$ nm. Simulations reveal that for $\Lambda > w$, the reflection in the interface of the slot waveguide and the MFE lens structure is considerably high. In the O-band, the return loss is as high as $-7$ dB and, consequently, the insertion loss increases to 1.9 dB. The lowest insertion loss, 0.76 dB, is obtained at $\lambda = 1435$ nm, at which the return loss reaches its minimum value. In the C-band, the average insertion loss is 1.16 dB and the cross talk levels are lower than $-16.0$ dB. The return loss in this band is lower than $-12$ dB. For the entire O, E, S, C, L, and U bands of optical communications, the cross talk levels are lower than $-15.1$ dB.

Finally, it is a good practice to compare the performance characteristics of the designed lens with other Si slot waveguide crossings. The insertion loss and cross talk of previous studies22,23,25 are better relative to the design presented in this paper. However, these designs only offer a solution for $2 \times 2$ slot waveguide crossings, whereas in this paper a $3 \times 3$ waveguide crossing is proposed. Moreover, the presented device can be simply expanded to support a higher number of waveguide crossings merely by increasing the size of the lens. Moreover, the footprint of our design is $2 \times 2 \mu m^2$, whereas the designs of Refs. 22, 23, and 25 have a considerably larger footprint. Other methods only offer a crossing angle of 90 deg with small deviations, whereas the crossing angle is a flexible parameter in our design. Last but not least, the design presented in this paper has the broadest bandwidth reported so far for Si slot waveguide crossings.
5 Conclusion
In this paper, a 3 × 3 Si slot waveguide crossing is proposed for the first time and numerically investigated by FDTD. We have successfully decreased the insertion loss of the simple intersection of three slot waveguides from 1.12 to 1.2 dB by utilizing the MFE lens as crossing medium. The proposed crossing is implemented by ring-based multilayer structure with a small footprint of 2 × 2 μm², which is considerably small compared to the available 2 × 2 crossings. The average insertion loss is 1.2 dB and crosstalk levels are below −15.1 dB in the entire O, E, S, C, L, and U bands of optical communication.

References

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