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# Low loss optical waveguide crossing based on octagonal resonant cavity coupling

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A waveguide crossing utilizing a high index contrast material system is presented. The structure is based on coupling with an octagonal resonant cavity inserted at the waveguide junction. It also employs four identical square metal strips placed at the four corners of the waveguide crossing. The spectral response of the structure calculated using the method of line numerical technique, in general, shows a high power transmission in the forward arm with sufficiently low crosstalk and fraction of radiated power.

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Waveguide crossings are integral part of any optical integrated circuits (OIC) as they allow interaction of many waveguides within a limited space. A variety of optical waveguide crossings have been reported in the literature which show high power transmission with little power coupling (crosstalk) from one waveguide into the other crossing waveguide while maintaining the optical symmetry of the structure on all four sides of the waveguide crossing. This includes waveguide crossings with both shallow[1-3] and large [4-7] intersecting angles. The reported waveguide crossings with shallow intersecting angles are generally large in dimensions and utilize low index contrast material system. This in turn imposes a maximum limit on the angle of the output arms with respect to the axis of the input arm. The waveguide crossings with large intersecting angle are of particular interest owing to their ability to confine light in a high index contrast material system which results in relatively compact structure size. Various techniques have been employed to enhance the performance of these structures, for instance, the well known perpendicular waveguide crossings with a 90° intersecting angle. In the following a brief review of some of the techniques reported in the literature will be presented. The perpendicular waveguide crossing reported in ref.[6] utilized holes drilled in the waveguide crossing to increase the power coupled to the forward arm while maintaining low modal reflectivity in the input arm. A square resonant cavity of appropriate dimensions was employed at the center of the waveguide crossing by ref.[7]. It is shown that by exciting the horizontally odd mode of the square cavity, the power coupled to the vertical arms (crosstalk) of the waveguide crossing is minimized. A multiple pair of waveguide cuts in the waveguide crossing was also introduced by ref.[7] which showed further improvement to the structure performance.

One aim of this letter is to enhance the performance of the waveguide crossing which utilizes a square resonant cavity, reported in ref.[7], by placing four identical square metallic strips at the four corners of the structure while maintaining the optical symmetry of the waveguide crossing. Finally, the square resonant cavity will be modified by etching evenly from all the four corners of the cavity forming an octagon. To the best of our knowledge, such a waveguide crossing with octagonal resonant cavity has been not reported in the literature. As will be seen later, with this structure, it is possible to obtain a very high power transmission in the forward arm while keeping the crosstalk and the fraction of the radiated power sufficiently low.

Two perpendicular waveguide crossing with a square resonant cavity at the waveguide junction, reported in ref.[7], is shown in Fig.1(a). In addition, Fig.1(a) also shows four identical square metallic strips placed evenly at the four corners of the structure. The waveguide core width is assumed to be $w$=0.2 μm which ensures the single mode of operation in the entire wavelength range of interest. The core and the cladding refractive indices are respectively 3.2 and 1.0 (air). The widths of the square cavity and the air gap which separates the square cavity from the four arms of the waveguide crossing are fixed at $s$= 360 nm and $g$= 80 nm, respectively, which are also reported in ref.[7]. The width of the metallic strip

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and its location from the waveguide ends are $a$= 700 nm and $b$= 200 nm, respectively. These tuned set of parameters are obtained through a repeated number of numerical simulations while maintaining the fraction of radiated power ($FPR$= 1- $R_1$- $T_2$-$T_3$- $T_4$) adequately low.

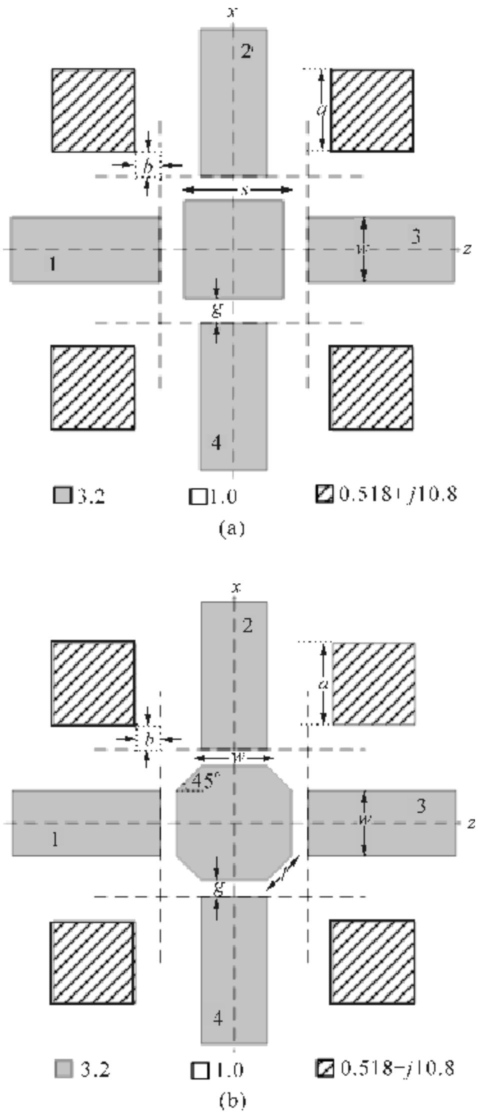

**Fig.1 Perpendicular optical waveguide crossing structures with (a) square cavity at the center (b) Octagonal cavity at the center. The structures also include four identical square silver strips placed evenly at the four corners of the structures**

By etching the square resonant cavity from all the four sides of the waveguide crossing shown in Fig.1(a), it is possible to obtain a waveguide crossing with much improved features. Fig.1(b) shows the proposed waveguide crossing with an eight sided resonant cavity forming an octagon with identical metallic strips placed evenly at the four corners of the structure. All the relevant waveguide parameters remain unaltered. The axes of the octagonal cavity are always assumed to coincide with the axes of the vertical and horizontal waveguides arms. The widths of the four sides of the octagonal cavity which are parallel to the four waveguide arms are chosen to be equal to the waveguide core width. This ensures excitation of the horizontally odd mode of the octagonal cavity which minimizes the power coupled to the vertical arms (crosstalk) of the waveguide crossing[8]. In this case, maximum power can be coupled to the forward arm with a low modal reflectivity in the input arm. The other four sides of the cavity are inclined at 45° with respect to the horizontal axis, as shown in Fig.1(b) with each side corresponding to a width $l$. The waveguide crossing shown in Fig.1 (b) requires tuning of the cavity and the metallic strip parameters. In this case also, these parameters are selected through a number of repeated simulations while monitoring the structure response.

The performance of these structures shown in Fig.1 will be demonstrated in this section. The well known method of lines (MOL) numerical technique is utilized for this purpose. The reader is referred to the cited references[9,10] which contain details of the two dimensional (2D) formulation of this method. The $TE_0$ fundamental mode is assumed to be incident on the waveguide junction from the input arm on the left hand side of the structures shown in Fig.1. Moreover, the spectral width $\Delta\lambda$ of the waveguide crossing structures are calculated based on the modal reflectivity curve ($R_1$) corresponding to the input arm, by taking an arbitrary measure of $R_l \leqslant 5 \times 10^{-3}$. The metallic strips are assumed to be made of silver with refractive index $0.518+j10.8$ at $\lambda$=1.55 μm. It is known that the complex refractive index of silver is highly wavelength dependent but it has been observed that accounting for the wavelength dependence of the refractive index of silver had a negligible effect on the calculated results. Therefore, the refractive index of silver is assumed to be independent of wavelength and is fixed at the above-indicated value. The modal reflectivity, modal transmissivity ($T_3$) corresponding to the forward arm and crosstalk ($T_2$, $T_4$) corresponding to the upper and the lower arm, are calculated using the MOL numerical technique.

Fig.2(a)-(c) show the spectral response of the waveguide crossing shown in Fig.1(a). In addition, Fig.2(a)-(c) also show the spectral response of the identical waveguide crossing without silver strips[7] for comparison purpose. The modal reflectivity ($R_1$), as shown in Fig.2(a), is sufficiently low throughout the wavelength range of the figure and generally similar to the ref.[7] attaining a value of $4.5\times 10^{-3}$ at$\lambda$=1.55 μm. Notice that the waveguide crossing show a much improved performance by attaining a substantially lower reflectivity value within its spectral width ($\Delta\lambda\approx$40 nm). Fig.2 (b) depicts that the modal transmissivity value $T_3$ corresponding to the forward arm has increased considerably in value compared with ref.[7] and maintains a generally flat response. The modal transmissivity value obtained in this case is about 0.99 at $\lambda$=1.55 μm compared with 0.96 which is reported in ref.[7]. An increase of approximately 0.03 in the modal transmissivity value ($T_3$) is observed in the entire wavelength range of the figure. The variation of the FPR and the crosstalk with wavelength is shown in Fig.2(c). The crosstalk curve obtained in this case is generally similar to that of ref.[7] and attains a value of < 0.0030 (-15.23 dB) throughout the wavelength range of interest. Thus, we may say that the insertion of the metallic strips at the four corners of the waveguide crossing structure has negligible effect on the crosstalk. However, the *FPR* curve shown in Fig.2(c) clearly reveals the superior performance of the structure. The *FPR* is < 0.0007(-31.55 dB) in the entire wavelength range of the figure compared with the *FPR* reported in ref.[7] which is about 0.0320 (-14. 95 dB). Thus, addition of the silver strips in the waveguide crossing structure has helped to reduce the *FPR* by approximately -16.60 dB. This enhanced performance may due to the radiative part of the field being suppressed by the use of silver strips placed at the four corners of the waveguide crossing. The power transmitted to the forward arm $T_3$ and the total structure loss ($TSL = R_1 + T_2 + T_4 + FPR$) obtained in this case are approximately $\leqslant$ 0.0105 (-19.79 dB), respectively, within the spectral width of the structure.

Next, the waveguide crossing is considered with octagonal cavity shown in Fig.1(b). The spectral response is calculated with the following set of tuned parameters: $l$ = 120 nm, $g$ =100 nm, $a$ = 700 nm and $b$ = 200 nm. Fig.3(a)-(c) show the resulting spectral response. In addition, Fig.3(a)-(c) also show the spectral response of the structure without inserting the metallic strips for comparison purpose. The modal reflectivity curve (Fig.3(a)) corresponding to the structure shown in Fig.1(b), is generally low in value in the entire wavelength range with a minimum value of approximately 3.9 × $10^{-8}$ at $\lambda$=1.55 μm. The spectral width in this particular case is $\Delta\lambda\approx$ 35 and again the modal reflectivity value shows a considerable improvement within the spectral width of the structure. Fig.3(b)-(c) show that nearly entire power is coupled to the forward arm ($T_3$ = 0.9990) of the structure while negligible power is coupled to the upper and the lower arms ($T_2$ = $T_4$ = 0.0002), at $\lambda$=1.55 μm. The utilization of octagonal resonant cavity has increased the modal transmissivity $T_3$ alone by 0.0100, and together with the insertion the silver strips (Fig.1(b)), $T_3$ has been further increased by 0.0400, in the entire wavelength range. Besides, insertion of octagonal resonant cavity instead of the square resonant cavity has reduced the cross talk of the structure substantially as depicted by Fig.3(c). The cross talk attains an extremely low value of approximately < 0.0004 (-34.56 dB) in the entire wavelength range of the figure which corresponds to a de-

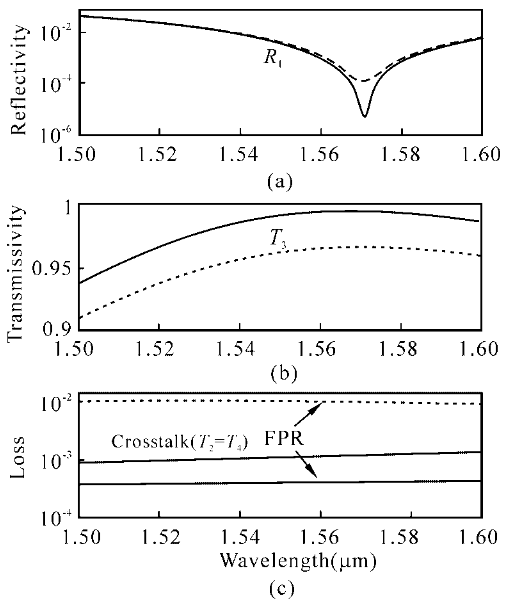

**Fig.2 Calculated spectral response of the waveguide crossing structure shown in Fig.1(a), represented by solid lines. The figure also includes the spectral response of the waveguide crossing structure shown in Fig.1(a) without the silver strips[7], represented by dash-dot lines.**

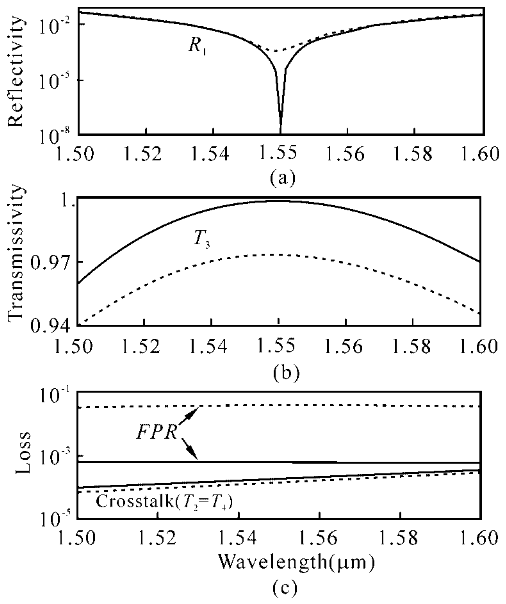

**Fig.3 Calculated spectral response of the waveguide crossing structure shown in Fig.1(b). The figure also includes the spectral response of the waveguide crossing structure shown in Fig.1(b) without the silver strips, represented by dash-dot lines.**

crease in crosstalk by -19.33 dB compared with the results of the previous reported structure (Fig.1(a)). As mentioned earlier, in this case also, the crosstalk has negligible effect on inserting the metallic strips in the structure. However, the *FPR*, shown in Fig.3(c), has considerably decreased in value with the insertion of metallic strips. The *FPR* corresponding to the structure of Fig.1(b) attains a sufficiently low value of approximately 0.0006 (-31.87 dB) at $\lambda$ =1.55 μm while for the case where no silver strips are inserted, the *FPR* is 0.0395 (-14.03 dB). In general, the *FPR* remains very low (<0.0007 (-31.55 dB)) in the entire wavelength range. For the octagonal resonant cavity waveguide crossing shown in Fig. 1(b), a total structure loss *TSL* = 0.0060 (-22.22 dB) is obtained whereas the power coupled to the forward arm $T_3$ attains a value of ⩾ 0.9940 in the entire range of the spectral width.

In conclusion, the perpendicular waveguide crossing with a resonant cavity at the centre and employing silver strips at the four corners of the structure is demonstrated. It is shown that by selecting suitable air gap width, cavity width, and the silver strip dimension and location, it is possible to obtain a high power transmission in the forward arm while maintaining the structure loss sufficiently low. For the square resonant cavity waveguide crossing with silver strips, a power transmission of 99% is obtained with a total structure loss of -19.8 dB within the spectral width. In the case of octagonal cavity waveguide crossing with silver strips, a power transmission of 99.4% is achieved within the spectral width while maintaining extremely low structure loss of -22.2 dB. In general, utilizing octagonal resonant cavity at the centre of the waveguide crossing has resulted in reduced crosstalk and the *TSL* by a factor of -19.33 dB and -2.5 dB, respectively. Moreover, in the particular case of $\lambda$ =1.55 μm, almost 100% power transmission is obtained in the forward arm with negligible *TSL*.

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