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SOI波导光传输损耗和端面耦合损耗的精确测量与理论分析

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摘 要：采用法布里-珀罗(Fabry-Perot)谐振腔（也称F-P腔）方法测试SOI波导光传输损耗及其与光纤的端面耦合损耗的测量精度，对具有相同尺寸长度为8.37 mm的三条SOI波导通道进行测量，得到SOI波导光传输损耗和端面耦合损耗的平均值与测量精度值，且测量精度偏差值很小。通过温度的自动控制扫描仪对另一条长度为12.5 mm的SOI波导进行三次重复测量，获得的传输损耗值和端面耦合损耗值相同，说明采用F-P腔方法获得的测量精度值很稳定。建立了SOI波导传输损耗测量精度da/a与F-P腔谐振输出功率极限值消光比的相对误差dt_M/t_M和SOI波导端面菲涅耳反射系数的相对误差dR/R之间关系的理论模型。模拟结果表明：改变SOI波导上、下包层和芯层折射率，对光传输损耗和波导-光纤端面耦合损耗的测试精度无影响。数值模拟结果与实验测试结果相一致。

关键词：SOI波导；法布里-珀罗腔；耦合损耗；传输损耗；测量精度
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Precision Measurement and Theoretical Analysis of SOI Waveguide Transmission Loss and Butt-coupling Loss

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Abstract: The method of Fabry-Perot resonant cavity (also called F-P cavity) is exploited to measure the optical transmission loss of SOI waveguides and the fiber-chip butt-coupling loss, with which three SOI waveguide channels having the same size and a length of 8.37 mm are measured. Then, the average value of SOI waveguide optical transmission loss/butt-coupling loss and the measurement accuracies are obtained, and the standard deviation of the measurements is very small. Another SOI waveguide with a length of 12.5 mm is measured using an automatic temperature control scanner and both the transmission losses and the butt-coupling losses of three repeated measurements are the same as one another, implying the stable measuring accuracies of F-P cavity method. The dual dependences of the measurement accuracy da/a of SOI waveguide transmission loss on the relative error dt_M/t_M of F-P cavity output extinction ratio and the relative error dR/R of the Fresnel reflection coefficient of SOI waveguide end-face are theoretically

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modelled. The simulation results show that the changes of SOI waveguide refractive index, the upper/lower cladding layers and core layer have no impacts upon the measurement accuracies of both the optical transmission loss and the fiber-chip coupling loss. The numerical simulation results are consistent with the experimental results.

Key words: SOI waveguide; Fabry-Perot cavity; Coupling loss; Propagation loss; Measurement accuracy

OCIS Codes: 130.0250; 130.2790; 130.3120; 130.3990

0 Introduction

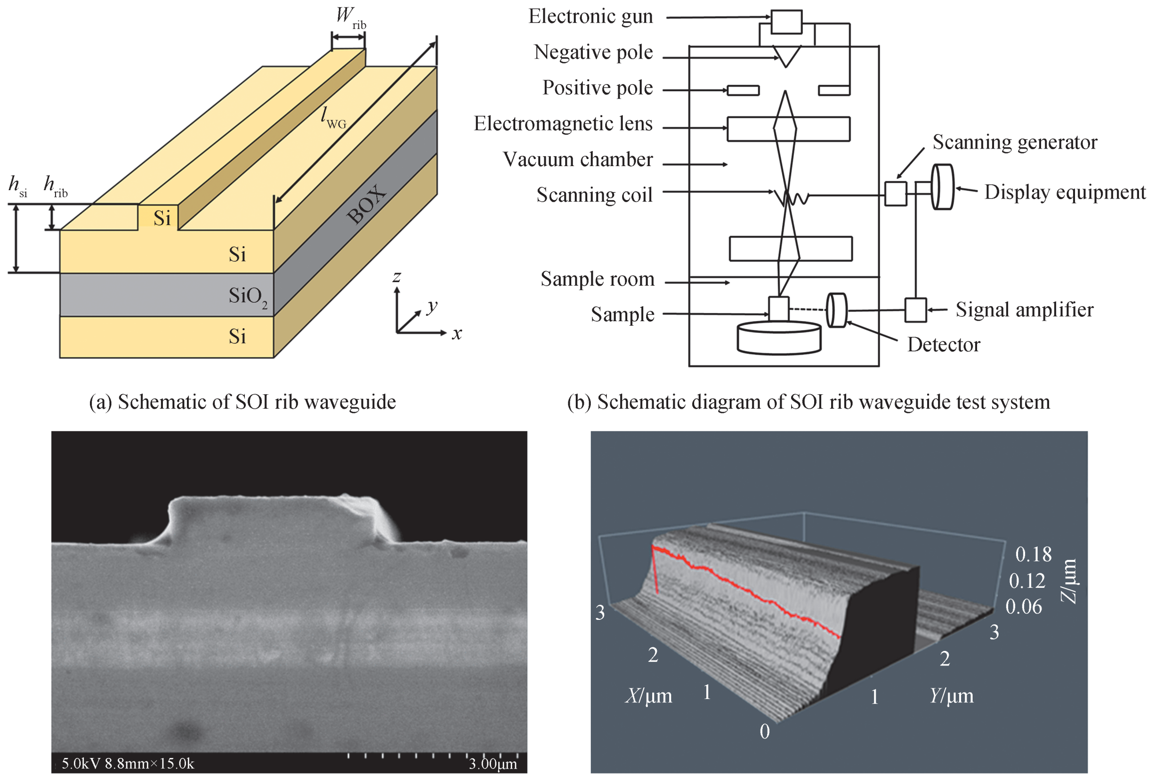
Silicon-On-Insulator (SOI) based photonics has spurred a great interest in the optical interconnection in modern computers, optical communications and microelectronic systems[1]. The application potential of silicon photonics and microelectronics integration is to closely link electronic functions with integrated optical functions to improve system performance[2]. SOI substrates are an attractive platform because the high refractive index contrast between the silicon core and the oxide cladding in the waveguide enables the waveguide cross-sectional area to submicron size, thus allowing the waveguide to bend at a smaller radius and resulting in the smaller and the highly integrated optical devices[3-5]. Further, by employing a standard Complementary Metal Oxide Semiconductor (CMOS) technology, the fabrication and production of SOI waveguide based Photonic Integrated Circuit (PIC) products could thus reach the effectively reducing costs[6].

Over the past decade, silicon photonics has attracted dense science research and product development around the world, and a number of optical SOI waveguide components have been demonstrated in the laboratory, including compact and low-loss SOI passive waveguide devices, high-speed silicon modulators, high-speed GeSi detectors, silicon Raman lasers, and thermal optical devices[7]. Although the silicon optoelectronic devices on the SOI platform have many advantages and have been developed to some extent, they still face some key technical problems in product development and application of devices, among which the unsolved problem is an accurate and effective SOI waveguide fiber-chip coupling loss measurement method[8-9]. Therefore, for the measurement accuracy of optical propagation loss of SOI waveguides and the fiber-chip coupling loss, it is very necessary to conduct the in-depth research on the measurement metrology as well as the measuring instruments[10-11]. In 1994, FEUCHTER T and THIRSTRUP C proposed to take the straight waveguide as a Fabry-Perot (F-P) cavity to realize the optical transmission loss of waveguide [12].

In the traditional cut-back method, the measuring accuracy is limited, so in this work the method of optical waveguide channel with two end-faces, Fabry-Perot cavity measuring method is exploited in order to make the optical waveguide transmission loss and the fiber-chip coupling loss. As a result, the high measurement precisions of both the optical transmission loss and the fiber-chip butting coupling loss of SOI waveguide are reached. Finally, the measurement accuracies of these two optical losses are theoretically modelled.

1 SOI waveguide structure and scanning electron microscopy tests

As an SOI platform, the BOX thickness was 2.0 μm and the silicon film thickness is h_{si}=1.5 μm. Then, the rib waveguides were fabricated as follows: the rib width and height are W_{rib}=4 μm and h_{rib}=0.5 um, respectively. The schematic of an SOI rib waveguide structure is shown in Fig. 1(a). A scanning electron microscope (SEM, Hitachi S-4800) is used to measure the polished-end quality of the waveguide and a schematic configuration of the SEM system is shown in Fig. 1(b), so an image of the end-face of SOI waveguide taken by the SEM system is shown in Fig. 1 (c), and a side-view image taken by a Confocal Laser Scanning Microscope (CLSM) is shown in Fig. 1(d). It can be clearly seen that the SOI waveguide etching angle is about 90°. The refractive index of BOX layer is 1.444, and the refractive index of silicon film is 3.45, an upper cladding layer having the refractive index of 1.444 is also deposited on the top of the rib waveguides, which is not drawn in Fig. 1(a). For TE mode, the effective refractive index is 3.414 6.



(a) Schematic of SOI rib waveguide

(b) Schematic diagram of SOI rib waveguide test system

(c) SEM image of the SOI rib waveguide end

(d) Side wall image of SOI rib waveguide

Fig. 1 SOI rib waveguide structure and test image

2 Measurements for optical transmission loss/fiber-chip butt-coupling loss of SOI waveguides

Measurements for the optical transmission loss of SOI waveguides were performed using a 1 550 nm light source and a single-mode SMF-28 fiber produced by Corning and further the fiber-chip butt-coupling loss of the waveguide was reached. At the coupling condition of SOI waveguide and optical fiber end-faces, the Fabry-Perot resonant cavity (also known as F-P cavity) was formed to respond to continuous phase modulation by light wave output, and the waveguide optical transmission loss was measured directly[12-13]. Then, the end faces of the SOI straight waveguides were grinded and polished, and in this process, the end faces of the waveguides were kept strictly perpendicular to the optical transmission direction of the waveguides to ensure that the two end faces of the chip form an ideal optical F-P cavity.

In the measurement experiment, a Positive Temperature Coefficient (PTC) heating sheet was used to heat the bottom of SOI waveguide, the effect of uniform change of SOI waveguide refractive index is achieved. PTC heating plate can effectively control the waveguide heating temperature, obtain the relationship between output power and heating temperature on the optical power detector, and then record the response of output power to temperature change. The optical transmission loss of SOI waveguide can be calculated by obtaining the extreme values of resonant output power amplitude, namely, the maximum and minimum values of the resonant output, which is given by

$$\alpha = -\frac{4.34}{l_{WG}} \ln\left(\frac{1-\sqrt{T_{min}/T_{max}}}{1+\sqrt{T_{min}/T_{max}}} \cdot \frac{1}{R}\right) \tag{1}$$

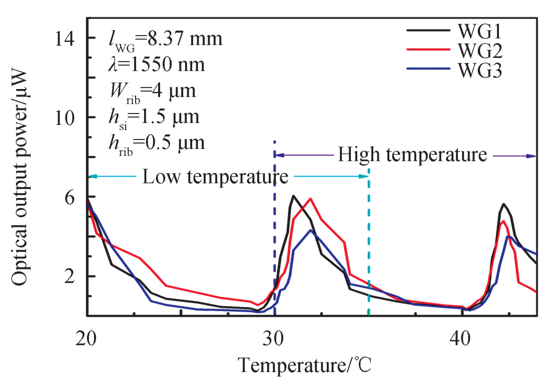
where l_{WG} represents the length of the waveguide channel, R represents the Fresnel reflection coefficient on both end faces of the waveguide[10-11], T_{max} and T_{min} represent the maximum and minimum values of transmission in the resonance curve respectively. If the effective refractive index of the guide wave mode of the waveguide is N_{eff}, then the Fresnel reflection coefficient formed by each end face of the waveguide obtained by the effective refractive index of the waveguide is:

$$R=\left(\frac{N_{\mathrm{eff}}-1}{N_{\mathrm{eff}}+1}\right)^2 \tag{2}$$

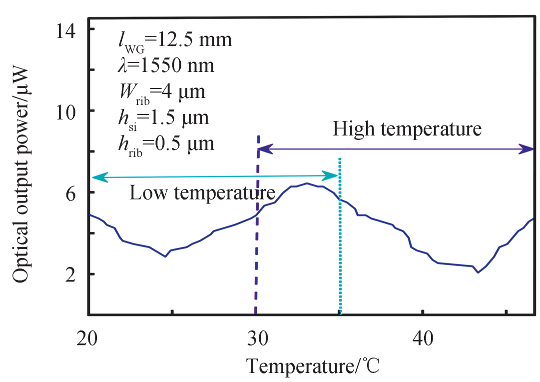
By testing the straight waveguide on the SOI chip, the response curve of the output power of an optical resonator varying with temperature was obtained. In the temperature range of 20 °C~45 °C, a semi-periodic response curve of the output power of optical resonator was obtained as shown in Fig. 2. In Fig. 2(a), the data of three waveguide channels with a length of 8.37 mm that were measured with the hand-set values of temperature. For transmission powers shown in Fig. 2(a), $T_{\min}$ values in the low and high temperature periods are set as $T_{\min}(L)$ and $T_{\min}(H)$, respectively, then among the three waveguides, these values are: for WG1, $T_{\min}(L)=0.270$ μW, $T_{\max}=6.053$ μW and $T_{\min}(H)=0.298$ μW; for WG2, $T_{\min}(L)=0.545$ μW, $T_{\max}=5.902$ μW and $T_{\min}(H)=0.5343$ μW; for WG3, $T_{\min}(L)=0.197$ μW, $T_{\max}=4.325$ μW, $T_{\min}(H)=0.321$ μW.

In order to ensure the validity of the measurement accuracy, each response curve is divided into two parts having the temperature ranges are 20℃~35℃ and 30℃~45℃, which have the same peak period. In the low temperature range, with the response curves of the output power of the three SOI waveguides shown in Fig. 2 and Eqs. (1) and (2), the optical transmission losses of the three SOI waveguides were obtained as 4.42 dB/cm, 3.01 dB/cm and 4.01 dB/cm, respectively. Further, through the total length of SOI waveguide channel: $l_{\mathrm{WG}}=$ 8.37 mm, the corresponding butt-coupling loss of SOI waveguide and fiber were obtained as 9.79 dB/facet, 10.37 dB/facet and 11.39 dB/facet, respectively. Finally, the average SOI waveguide transmission loss is 3.81 dB/cm, and the Standard Deviation (SD) value is ±0.59 dB/cm, that is, the measurement accuracy is ±15.5%. The average SOI waveguide-fiber butt-coupling loss is 10.52 dB/facet, and the SD value is ±0.66 dB/facet, that is, the measurement accuracy is ±6.3%. In the same manner, in the high temperature range, the output power response curves of the three waveguide channels were tested, and the optical transmission losses of the three waveguides were obtained as 3.94 dB/cm, 3.41 dB/cm and 3.48 dB/cm, respectively. Then the corresponding SOI waveguide and fiber butt-coupling losses were obtained as 9.99 dB/facet, 10.22 dB/facet and 11.62 dB/facet, respectively. Finally, the average SOI waveguide optical transmission loss is 3.61 dB/cm, and the SD value is ±0.24 dB/cm, that is, the measurement accuracy is ±1.9%. The average SOI waveguide-fiber butt-coupling loss is 10.61 dB/facet, and the SD value is ±0.72 dB/facet, that is, the measurement accuracy is ±6.8%. As can be seen from the above measurement results, the SD values of both the optical transmission loss and the butt-coupling loss are very small, implying the high measurement precisions in both the low and the high temperature regions. It is shown that the change of temperature has no effect on the measurement accuracy of the optical transmission loss and the butt-coupling loss of SOI waveguide.

Fig. 2(b) measures the data of the waveguide channel using the automatically controlled scanning value of temperature. For the second chip of waveguide with a length of 12.5 mm, the insertion loss of 24.44 dB was measured, then with the Fig. 2(b) and Eqs. (1) and (2) and from both the lower and the higher temperature ranges, by repeating three measurement we obtained the corresponding transmission losses of 3.33, 3.91, 3.50 dB/cm. Then the corresponding SOI waveguide-fiber butt-coupling loss values were obtained to be 10.56 dB/facet,



(a) The temperature values were set one by one



(b) The temperature values were scanned of a voltage scanning

Fig. 2 Propagation losses test of three SOI waveguides and the responses of F-P cavity formed by the waveguide channel to temperature change, where the lower temperature ranges are 20 ℃~35 ℃, the high temperature range are 30 ℃~45 ℃

10.27 dB/facet and 10.47 dB/facet, respectively. From the above three measured values, the average transmission loss of 3.58 dB/cm was obtained, leading to the SD value of ± 0.24 dB/cm, namely, $\pm 6.7\%$. Similarly, the average fiber butt-coupling loss of 10.43 dB/facet was obtained, leading to the SD value of 0.12 dB/facet, namely, $\pm 1.2\%$. It turns out that, with the auto-control scanning of temperature, the F-P response method investigated in this work is very reliable and the measured results are accurate.

In the measurements of physical parameters, the efficiencies of the measure parameters are not only evaluated in measurement principle, but also in measurement accuracy. It can be found from Eqs.(1) and (2) that Fresnel reflection coefficient R is a key parameter in the equations, which is determined by the effective refractive index N_{eff} of the guided wave mode. As shown in Fig. 2, the response curve of WG1 optical output power to temperature was selected, and the corresponding core layer refractive index is 3.45, and the upper and lower cladding refractive index is set to be three different values: 1.44, 1.45 and 1.46, and the effective refractive index N_{eff} is 3.414 6. Therefore, from the Eqs. (1) and (2), it could be seen that the waveguide-fiber end-face coupling loss value is unchanged. For three different core layer refractive index values: 3.44, 3.45 and 3.46, the effective refractive index N_{eff} obtained is respectively 3.404 5, 3.414 6 and 3.424 7, with an average value of 3.414 6 and a SD value of $\pm 0.24\%$. It turns out that the variation of refractive index of upper and lower cladding layers does not affect the measurement accuracy of SOI waveguide optical transmission loss and chip-fiber butt-coupling loss, while for the variation of refractive index of core layer, the influence on the measurement accuracy of SOI waveguide optical transmission loss and fiber-chip butt-coupling loss is also ignorable.

3 Theory and numerical simulation of measurement accuracy

In order to further analyze the measurement accuracy of fiber-waveguide butt-coupling loss. First, the key parameters in the relative error Eq.(1) of the F-P cavity resonant output power maximum/minimum extinction ratio are discussed. The key parameters of resonance output power maximum value T_{max} and the minimum value T_{min}, set $t_M = \sqrt{T_{min}/T_{max}}$ as F-P cavity output extinction ratio, the waveguide end-face caused Fresnel reflection coefficient affects the measuring accuracy of SOI waveguide optical transmission loss in the measurement due to the errors of T_{max} and T_{min}, R could produce an uncertainty. Therefore, Eq. (1) is changed to

$$\alpha = -\frac{4.34}{l_{WG}} \ln\left(\frac{1-t_M}{1+t_M} \cdot \frac{1}{R}\right) \tag{3}$$

With t_M and R as variables, take the derivative of the optical wave transmission loss coefficient α defined in Eq. (3) to obtain the error analysis function as defined by

$$\mathrm{d}\alpha = \left(-\frac{4.34}{l_{WG}}\right)\left(\frac{1+t_M}{1-t_M}\right) \times \left[\frac{2\mathrm{d}t_M}{1-t_M} - \frac{1+t_M}{1-t_M}\frac{\mathrm{d}R}{R}\right] \tag{4}$$

Therefore, the change of effective refractive index of guided wave mode affects the precision of Fresnel reflection coefficient dR, and the changes of both T_{max} and T_{min} of F-P cavity resonant output curve with temperature affect the extinction ratio dt_M value. Furthermore, dR and dt_M determine the measurement accuracy of optical waveguide transmission loss defined by Eq.(4). The relative error expression of Fresnel reflection coefficient generated by the waveguide end-face is obtained by a differential equation as defined by

$$\frac{\mathrm{d}R}{R} = \frac{4N_{eff}}{(N_{eff}+1)\cdot(N_{eff}-1)} \cdot \frac{\mathrm{d}N_{eff}}{N_{eff}} \tag{5}$$

In the similar form, the relative error expression of extinction ratio of T_{max} and T_{min} values of F-P cavity resonant output power is defined by

$$\frac{\mathrm{d}t_M}{t_M} = \frac{1}{2}\left(\frac{\mathrm{d}T_{min}}{T_{min}} - \frac{\mathrm{d}T_{max}}{T_{max}}\right) \tag{6}$$

Therefore, substituting Eq. (6) into Eq. (4) yields the measurement accuracy expression of SOI waveguide optical transmission loss defined by

$$\frac{\mathrm{d}\alpha}{\alpha}=\frac{\dfrac{1+t_{\mathrm{M}}}{1-t_{\mathrm{M}}}}{\ln\left(\dfrac{1-t_{\mathrm{M}}}{1+t_{\mathrm{M}}}\cdot\dfrac{1}{R}\right)}\times\left[\frac{2t_{\mathrm{M}}}{1-t_{\mathrm{M}}}\frac{\mathrm{d}t_{\mathrm{M}}}{t_{\mathrm{M}}}-\frac{1+t_{\mathrm{M}}}{1-t_{\mathrm{M}}}\frac{\mathrm{d}R}{R}\right] \tag{7}$$

It can be seen from Eq. (7) that the measurement accuracy of SOI waveguide transmission loss $\mathrm{d}a/a$ is a function of the relative error $\mathrm{d}t_{\mathrm{M}}/t_{\mathrm{M}}$ of the F-P cavity resonant output extinction ratio and the relative error $\mathrm{d}R/R$ of the Fresnel reflection coefficient at the end of SOI waveguide. However, the $\mathrm{d}R/R$ and $\mathrm{d}t_{\mathrm{M}}/t_{\mathrm{M}}$ can not be directly tested. So, the effect of the effective refractive index N_{eff} on $\mathrm{d}R/R$ and the effect of $\mathrm{d}T_{\max}/T_{\max}$ and $\mathrm{d}T_{\min}/T_{\min}$ on $\mathrm{d}t_{\mathrm{M}}/t_{\mathrm{M}}$ are tested, these effects on the $\mathrm{d}R/R$ and $\mathrm{d}t_{\mathrm{M}}/t_{\mathrm{M}}$ are transferred onto the transmission loss measurement accuracy $\mathrm{d}a/a$.

The corresponding relationship between the relative error $\mathrm{d}R/R$ of Fresnel reflection coefficient and the effective refractive index N_{eff} of guided wave mode is obtained from Eq. (5) as shown in Fig. 3. As can be seen from Fig. 3, when the effective refractive index increases from 3.24 to 3.44, the relative error of Fresnel reflection coefficient decreases from 1.37% to 1.27%, indicating that the relative error of Fresnel reflection coefficient can be reduced by increasing the effective refractive index.

With Eq. (6), the dependence of the relative error $\mathrm{d}t_{\mathrm{M}}/t_{\mathrm{M}}$ of extinction ratio of SOI waveguide F-P cavity resonant output on the maximum $\mathrm{d}T_{\max}/T_{\max}$ and the minimum $\mathrm{d}T_{\min}/T_{\min}$ is obtained as shown in Fig. 4. It can be noticed that, when the $\mathrm{d}T_{\min}/T_{\min}$ is positive and $\mathrm{d}T_{\max}/T_{\max}$ is negative, the $\mathrm{d}t_{\mathrm{M}}/t_{\mathrm{M}}$ positive direction increases, when the $\mathrm{d}T_{\min}/T_{\min}$ negative and $\mathrm{d}T_{\max}/T_{\max}$ is positive, $dt_{\mathrm{M}}/t_{\mathrm{M}}$ to negative direction. The value of $\mathrm{d}t_{\mathrm{M}}/t_{\mathrm{M}}$ is the average difference between $\mathrm{d}T_{\max}/T_{\max}$ and $\mathrm{d}T_{\min}/T_{\min}$ no matter in the positive direction or the negative direction $\mathrm{d}t_{\mathrm{M}}/t_{\mathrm{M}}$ is. It is shown that change of either the $T_{\max}$ or $T_{\min}$ of SOI waveguide F-P cavity resonant output power

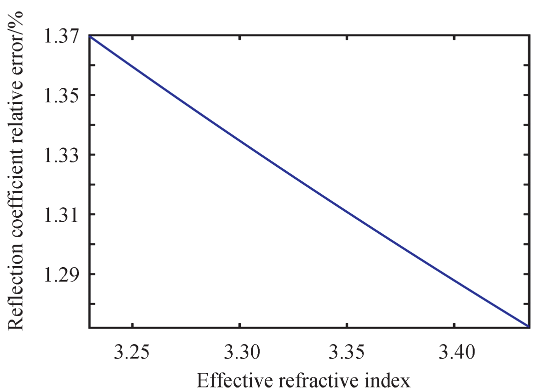


Fig. 3 The relation between the relative error of Fresnel reflection coefficient and the effective refractive index of guided wave mode.

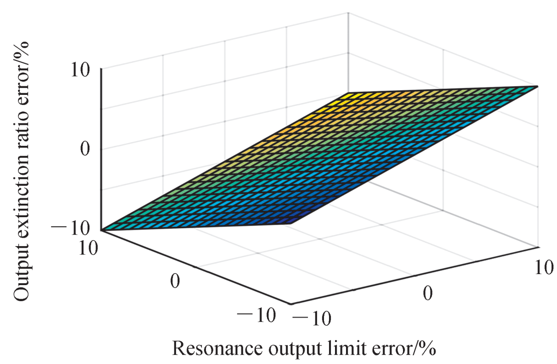


Fig. 4 The influence of the maximum and minimum relative error of SOI waveguide F-P cavity response to temperature change on extinction ratio relative error

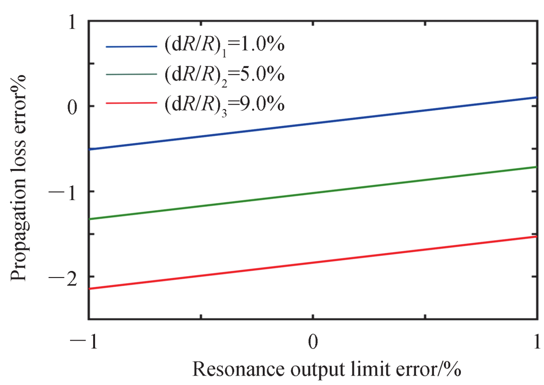


Fig. 5 The measurement accuracy of SOI waveguide transmission loss and the extinction ratio of F-P cavity output value correspond to three different reflectivity error values

has no influence on the relative error $\mathrm{d}t_M/t_M$ of the extinction ratio.

By setting $T_{max}=0.9$, $T_{min}=0.1$ and $\mathrm{d}R/R$ values as 1.0%, 5.0% and 9.0%, the dual dependence of $\mathrm{d}a/a$ on $\mathrm{d}t_M/t_M$ and $\mathrm{d}R/R$ for the waveguide optical transmission loss measurement accuracy is obtained by using Eq. (7) as shown in Fig. 5, where the blue, green and red lines are 1.0%, 5.0% and 9.0% respectively. Note that the error of $\mathrm{d}R/R$ between 1.0% and 9.0% has caused an optical transmission loss measurement accuracy of about 1.5%. In Sec. 2, when the effective refractive index N_{eff} is 3.404 5, 3.414 6 and 3.424 7, the average value is 3.414 6 with ±0.24%. Then, it can be seen from Figs. 4 and 5 that the change of refractive index of silicon core has no influence on the measurement accuracy of transmission loss. Therefore, changing the refractive index of the upper, lower and core layers of SOI waveguide has no effect on the measurement accuracy of optical transmission loss and fiber-waveguide butt-coupling loss.

4 Conclusion

The F-P cavity method is used to measure the output power of three straight waveguides in response to temperature change. By measuring the optical transmission loss of three SOI waveguides, the mean value of the effective optical transmission loss and the butt-coupling loss and the measurement accuracy values are obtained. The measurement accuracies of SOI waveguide optical transmission loss and butt-coupling loss do not change with temperature. The theoretical model and simulation of measurement accuracy show that the refractive index changes of the upper, lower cladding and core layers have no influence on the measurement accuracies of both the SOI waveguide optical transmission loss and the waveguide-fiber butt-coupling loss, which is consistent with the experimental results of measurement accuracy. The F-P cavity measurement method combining the theoretical model and numerical simulation is expected to be applied in industry.

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