A novel polymer-on-silicon Mach-Zehnder interferometer optical filter and the performance analysis based on spectrum-periodized theory*

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The analysis on the traditional asymmetric Mach-Zehnder interferometer (AMZI) optical filter based on two 3 dB directional couplers (DCs) shows that by adding an additional nonlinear phase generated by phase-generating coupler (PGC) to the original phase difference of the AMZI, its non-periodic frequency response can be modified, and a strictly periodic spectrum can be obtained. A novel structure of the AMZI filter using two PGCs before and after the AMZI region is proposed. With the needed free spectrum range (FSR) of 20 nm, the design and optimization of the device are performed using polymer SU-8 as the core and PMMA-GMA as the buffer. Though the insertion loss (IL) gets larger than that of the traditional AMZI filter, the FSR is nearly uniform as the expected period of 20 nm.

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In both dense wavelength-division multiplexing (DWDM) and coarse wavelength-division multiplexing (CWDM) systems[1-3], optical filters are key components which are widely used in optical signal processing as well as other devices like optical switches[4, 5]. A common and efficient structure for achieving satisfactory filtering performance is Mach-Zehnder interferometer (MZI)[6-8]. In CWDM systems, since the frequency spacing between two neighboring channels is greatly more than 200 GHz[9,10], the frequency response in such circumstance should be periodic over a wide wavelength range. For the asymmetric MZI (AMZI) filtering structure based on two 3 dB directional couplers (DCs) under the designed central wavelength, a fixed phase difference is created between two branches. Noticing that the generated phase of the two 3 dB DCs is constant, as the operation wavelength changes within a wide range, the phase difference of the AMZI is not periodic with wavelength, which leads to non-periodic output spectrum. To enable the MZI filter to possess periodic frequency response with respect to wavelength, in this paper, we propose a novel filtering structure by using two symmetric phase-generating couplers (PGCs) both before and after the AMZI. The spectrum-periodized theory on AMZI and the related formulas are described, and then an AMZI optical filter based on such theory is designed and simulated.

The traditional polymer AMZI filter consisting of two 3 dB DCs is shown in Fig.1(a), where d_2 and L_{DC} are the coupling gap and coupling region length of the two 3 dB DCs, respectively. In the AMZI region, let ΔL be the optical path difference between the upper and lower waveguides. The input power and output power are P_{in} and P_{out}, respectively. The designed rib waveguide structure is shown in Fig.1(b), where the negative photoresist polymer SU-8 and polymer PMMA-GMA are used as the core and upper/under buffer layers, respectively[11]. The refractive indices of SU-8 and PMMA-GMA are denoted by n_1 and n_2, respectively, and their bulk amplitude attenuation coefficient are denoted by α_1 and α_2, respectively. The refractive index of the upper confined layer air is n_3=1.0, and its bulk amplitude attenuation coeffi-

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cient is α_3=0. We investigate their refractive indices and extinction coefficients using an ellipsometer, as shown in Fig.2.

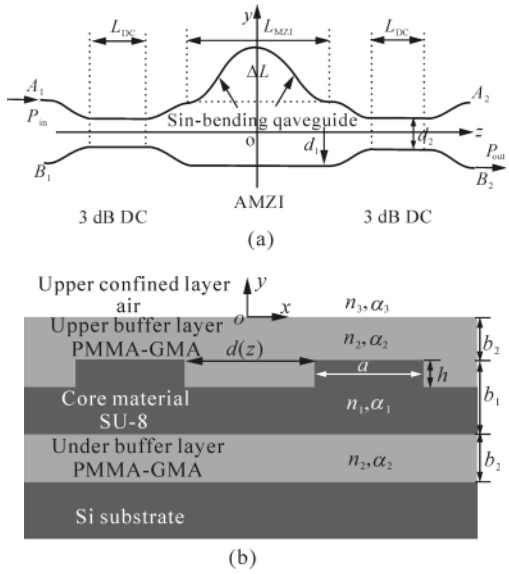

Fig.1 (a) Traditional polymer AMZI filter consisting of two 3 dB DCs, and (b) designed rib waveguide structure of the AMZI filter over the cross-section at *z* axis

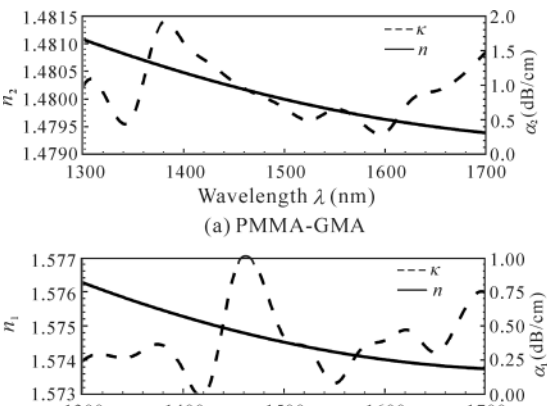

Fig.2 Measured refractive indices and extinction coefficients of two polymers

In terms of our designed technique on rib waveguide structure[12,13] under λ_c=1550 nm, and assuring only the fundamental mode E_{00}^{y} propagating in the waveguide, we select a=4.0 μm, b_1=2.0 μm, h=0.5 μm and b_2=3.0 μm. The mode effective refractive index and amplitude loss coefficient are $n_{\text{effo}}(\lambda_c)$=1.5469 and $\alpha(\lambda_c)$=0.5846 dB/cm, respectively. For enhancing the coupling effect between the two waveguides of DC and decreasing that between the two arms of MZI, the coupling gaps are taken as d_1 = 30 ìm and d_2 = 3.0 ìm, respectively. In this case, the coupling length of each DC is $L_0(\lambda_c)$=1019 ìm, and the coupling coefficient between the two MZI arms is as small as $K_{\text{MZI}}(\lambda_c)\leqslant 0.0004\ \text{m}^{-1}$.

When a pulse signal is applied at the input port of the filter, the output signal related to t, which is also named time-domain impulse response, is defined by $x(t)$, and its sampling discrete signal is $x(nT_s)$, where T_s is the sampling period. So the transfer function $X(\omega)$ in frequency-domain of the filter, which is also the Fourier transformation of the discrete time-domain impulse response, can be obtained by

$$X(\omega)=\sum_{n=0}^{N}x(nT_s)\exp(-\mathrm{j}n\omega T_s)\quad , \tag{1}$$

where ω is the lightwave circular frequency. When we take

$$T_s=\Delta L\ n_{\text{eff0}}/c\quad , \tag{2}$$

where n_{eff0} is the effective refractive index of the fundamental mode, which depends on wavelength, and c is the lightwave velocity in vacuum, Eq.(1) is further written as

$$X(\omega)=\sum_{n=0}^{N}x_n\exp[-\mathrm{j}n\omega\Delta Ln_{\text{eff}\,0}/c]\,, \tag{3}$$

where $x_n=x(nT_s)$. Noticing that $c=\omega\lambda/(2\pi)$, Eq. (3) is finally expressed as

$$X(\lambda)=\sum_{n=0}^{N}x_n\exp\{-\mathrm{j}n2\pi[\Delta Ln_{\text{eff}\,0}(\lambda)/\lambda]\}\ . \tag{4}$$

We can see from Eq.(4) that since $\Delta Ln_{\text{eff0}}(\lambda)/\lambda$ is not a fixed value, $X(\lambda)$ can not possess strictly periodic relation with wavelength λ.

For the convenience in the following analysis, define $f(\lambda)$ as

$$f(\lambda)=n_{\text{eff0}}(\lambda)/\lambda\ . \tag{5}$$

Then the frequency response given by Eq. (4) is modified to

$$X(\lambda)=\sum_{n=0}^{N}x_n\exp\{-\mathrm{j}n2\pi[\Delta Lf(\lambda)]\}. \tag{6}$$

If an extra phase difference $\varphi(\lambda)$ related to wavelength is added in Eq.(6), we obtain

$$X(\lambda)=\sum_{n=0}^{N}x_n\exp\{-\mathrm{j}n2\pi[\Delta Lf(\lambda)-\varphi(\lambda)]\}\ . \tag{7}$$

With the requirement that $X(\lambda)$ should be periodic with λ, $\varphi(\lambda)$ can be taken as

$$\varphi(\lambda)=\Delta Lf(\lambda)+\frac{\lambda}{\Delta\lambda}-\left(m+\frac{\lambda_c}{\Delta\lambda}\right)\ , \tag{8}$$

where λ_c is the designed central operation wavelength, m is an integer, and $\Delta\lambda$ is the designed free spectrum range (FSR). Therefore, $X(\lambda)$ is transformed to

$$X(\lambda)=\sum_{n=0}^{N}x_n\exp\left(\mathrm{j}n2\pi\frac{\lambda-\lambda_c}{\Delta\lambda}\right). \tag{9}$$

For any integer p, we can easily prove $X(\lambda+p\Delta\lambda)=X(\lambda)$, which shows that $X(\lambda)$ reveals the uniform wavelength spacing of $\Delta\lambda$. We choose m =0. Therefore, the added phase $\varphi(\lambda)$ given by Eq.(8) can be transformed to

$$\varphi(\lambda)=\Delta Lf(\lambda)+(\lambda-\lambda_c)/\Delta\lambda \ . \tag{10}$$

Eq.(10) means that for realizing periodic frequency response, an extra nonlinear phase $\varphi(\lambda)$ should be added to the phase difference of the MZI for phase compensation.

Fig.3 presents the schematic diagram of the designed AMZI optical filter, which consists of two serial-cascaded PGCs both before and after the AMZI region. The designed PGC contains three DCs and two optical delay lines (ODLs). For the i-th DC, θ_i is the angular expression of the wavelength-dependent amplitude coupling ratio, and l_i is its coupling region length.

$$\theta_i(\lambda)=\pi l_i/[2L_0(\lambda)] \ , \tag{11}$$

where $L_0(\lambda)$ indicates the coupling length of the DC at λ. For the i-th ODL, δl_i is the difference between the optical paths of upper-branch and under-branch.

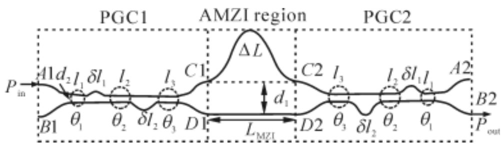

Fig.3 Schematic diagram of the designed AMZI optical filter

According to our previous report on the EO switches based on PGCs[14], the transfer matrixes of PGC1 and PGC2 can be written as

$$\boldsymbol{T}_{\mathrm{PGC1}}(\lambda)=\begin{pmatrix}A & -B^*\\ B & A^*\end{pmatrix},\ \boldsymbol{T}_{\mathrm{PGC2}}(\lambda)=\begin{pmatrix}A & B\\ -B^* & A^*\end{pmatrix} \ , \tag{12}$$

where A and B can be determined from $\begin{pmatrix}A & -B^*\\ B & A^*\end{pmatrix}=\boldsymbol{T}_{\mathrm{DC}}^{3}\prod_{i=2}$ $\boldsymbol{T}_{\mathrm{ODL}}^{i}\boldsymbol{T}_{\mathrm{DC}}^{i}$, and for the first PGC, the transfer matrixes of the i-th DC and i-th ODL are

$$\boldsymbol{T}_{\mathrm{DC}}^{i}(\lambda)=\begin{pmatrix}\cos\theta_i & -\mathrm{j}\sin\theta_i\\ -\mathrm{j}\sin\theta_i & \cos\theta_i\end{pmatrix} \ , \tag{13}$$

$$\boldsymbol{T}_{\mathrm{ODL}}^{i}(\lambda)=\begin{pmatrix}\exp[-\mathrm{j}\pi\delta l_i n_{\mathrm{eff0}}(\lambda)/\lambda] & 0\\ 0 & \exp[\mathrm{j}\pi\delta l_i n_{\mathrm{eff0}}(\lambda)/\lambda]\end{pmatrix}. \tag{14}$$

With the default multiplicative factor of 2π, the absolute value of the phase difference $\varsigma(\lambda)$ in the AMZI region resulting from the optical path difference ΔL can be expressed as

$$\varsigma(\lambda)=\Delta L n_{\mathrm{eff0}}(\lambda)/\lambda=\Delta Lf(\lambda) \ , \tag{15}$$

where $f(\lambda)=n_{\mathrm{eff0}}(\lambda)/\lambda$ is defined by Eq.(6). The amplitude transfer matrix of the AMZI is

$$\boldsymbol{T}_{\mathrm{MZI}}(\lambda)=\begin{bmatrix}\exp(-\mathrm{j}\pi\varsigma) & 0\\ 0 & \exp(\mathrm{j}\pi\varsigma)\end{bmatrix} \ . \tag{16}$$

Let the light with an original amplitude of $R_1\neq 0$ input into port $A1$ only, so the output amplitudes R_2 and S_2 from ports $A2$ and $B2$ are

$$\begin{pmatrix}R_2\\ S_2\end{pmatrix}=R_1\begin{pmatrix}A^2\exp[-\mathrm{j}\pi\Delta Lf(\lambda)]+B^2\exp[\mathrm{j}\pi\Delta Lf(\lambda)]\\ -AB^*\exp[-\mathrm{j}\pi\Delta Lf(\lambda)]+A^*B\exp[\mathrm{j}\pi\Delta Lf(\lambda)]\end{pmatrix}. \tag{17}$$

Assume ϕ_A=arg(A), ϕ_B=arg(B) and $P_0=|R_1|^2$. From Eq.(17), the output power P_{out} of the optical filter is finally expressed as the following form

$$P_{\mathrm{out}}(\lambda)=10\lg\{4|A|^2|B|^2\sin^2[(\phi_A-\phi_B)-\pi\Delta Lf(\lambda)]\}-2\alpha(\lambda)L_{\mathrm{total}} \ , \tag{18}$$

where $\alpha(\lambda)$ is the mode amplitude optical loss, L_{total} is the total propagation waveguide length, and $\phi_A-\phi_B$ can be treated as the compensated phase by two PGCs. According to spectrum-periodized theory (Eq.(10)), to realize periodic frequency response, the following phase compensation condition should be satisfied

$$\phi_A(\lambda)-\phi_B(\lambda)=\varphi^*(\lambda)=\pi\Delta Lf(\lambda)+\pi(\lambda-\lambda_c)/\Delta\lambda \ . \tag{19}$$

Besides, from Eq.(18), to achieve a high extinction ratio, we obtain the following extinction ratio compensation condition

$$|A(\lambda)B(\lambda)|=\frac{1}{2} \ . \tag{20}$$

Take the FSR as $\Delta\lambda$ = 20 nm, and the designed wavelength range as 1400−1600 nm. The designed central wavelength of the i-th channel for the filter is

$$\lambda_{c,i}^{0}=1550+\Delta\lambda/2+i\times\Delta\lambda \ ,\ (i=\cdots,-2,-1,0,1,2,\cdots) \ , \tag{21}$$

and the insertion loss (IL) at $\lambda^0_{c,i}$ of the i-th channel is

$$IL_i=P_{\mathrm{out}}(\lambda^0_{c,i}) \ . \tag{22}$$

Assume that $l_1=l_2=l_3\equiv l_0$, then $\theta_1=\theta_2=\theta_3\equiv\theta_0$. The coupling ratios A and B can be written as

$$A=\cos[\pi(\delta l_1+\delta l_2)f]\cos(l_0g\pi/2)\cos(l_0g\pi)-\cos[\pi(\delta l_1-\delta l_2)f]\times\sin(l_0g\pi/2)\sin(l_0g\pi)-\mathrm{j}\{\sin[\pi(\delta l_1-\delta l_2)f]\cos(l_0g\pi/2)\}, \tag{23}$$

$$B=-\sin[\pi(\delta l_1-\delta l_2)f]\sin(l_0g\pi/2)-\mathrm{j}\{\cos[\pi(\delta l_1+\delta l_2)f]\times\cos(l_0g\pi/2)\sin(\pi l_0g)+\cos[\pi(\delta l_1-\delta l_2)f]\sin(l_0g\pi/2)\cos(\pi l_0g)\} \ , \tag{24}$$

where $f(\lambda)=n_{\mathrm{eff0}}(\lambda)/\lambda$, $g(\lambda)=1/L_0(\lambda)$, and the parameters l_0, δl_1 and δl_2 need to be decided.

For realizing the phase and extinction ratio compensation conditions, the optimized parameters are $\delta l_1 = 3.06\lambda_c$, $\delta l_2 = -2.90\lambda_c$, $l_1=l_2=l_3=l_0=0.67\ L_0(\lambda_c)$, and $\Delta L=44\lambda_c$. We find from Fig.4 that the designed PGC-based AMZI filter shows favorable periodic frequency response due to the agreement between $\phi_A-\phi_B$ and φ^*. However, when λ is larger than 1550 nm, $|A(\lambda)||B(\lambda)|$ does not approach to $\frac{1}{2}$, so the ILs of channels #0 and #1 increase.

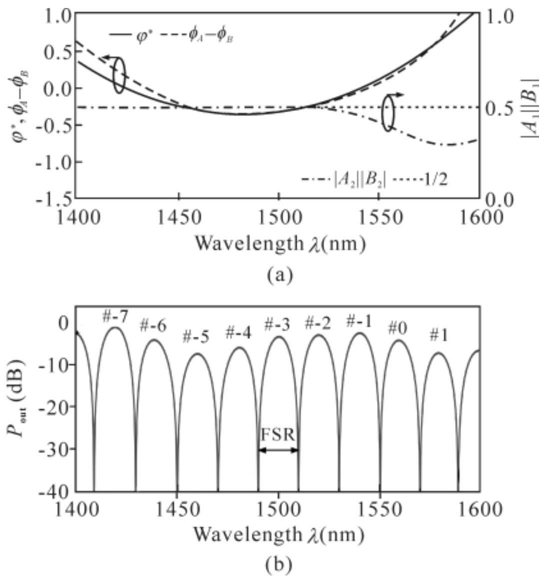

Fig.4 Curves of (a) the required phase φ^*, compensated phase $\phi_A-\phi_B$ and $|A(\lambda)||B(\lambda)|$ versus wavelength λ, and (b) the normalized output power P_{out} versus wavelength λ for the PGCs-based AMZI filter

As a comparison, we plot Fig.5, where $\Delta L=44\lambda_c$. We find that as λ changes, the traditional AMZI filter reveals non-periodic frequency response, and for each channel, the FSR increases from 18 nm to 23 nm as the channel number changes from #-7 to #1. From the comparison in Fig.5(b), by using the PGC for phase compensation, the designed PGCs-based AMZI filter reveals nearly strictly periodic frequency response.

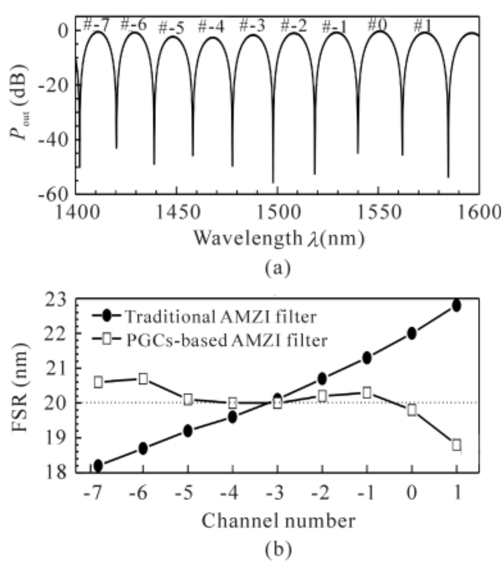

Fig.5(a) Curve of the output power P_{out} versus the operation wavelength λ for the traditional AMZI filter, and (b) comparison of the FSR between the traditional AMZI filter and the PGCs-based AMZI filter

In this work, a novel structure of the AMZI filter by using two PGCs before and after the AMZI region is proposed. For achieving periodic frequency response, the phase compensation condition and the extinction ratio compensation condition are reached. A PGCs-based AMZI filter with the designed FSR of 20 nm is optimized and simulated using the presented technique. The filter shows more strictly periodic FSR and smaller IL than the traditional device. The proposed filtering structure with uniform wavelength spacing between two neighboring channels of about tens of nanometers shows potential applications in CWDM communication networks.

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