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1.55μm Fabry-Perot Thermo-Optical Tunable Filter with Amorphous-Si as Cavity*

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Abstract: A 1.55μm Fabry-Perot (F-P) thermo-optical tunable filter is fabricated. The cavity is made of amorphous silicon (a-Si) layer grown by electron-beam evaporation technique. Due to the excellent thermo-optical property of a-Si, the refractive index of the F-P cavity will be changed by heating; the transmittance resonant peak will therefore shift substantially. The measured tuning rang is 12nm, FWHM (full-width-at-half-maximum) of the transmission peak is 9nm, and heating efficiency is 0.1K/mW. The large FWHM is mainly due to the non-ideal coating deposition and mirror undulation. Possible improvements to increase the efficiency of heating are suggested.

Key words: thermo-optical effect; Fabry-Perot; tunable filter; a-Si
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1 Introduction

WDM (wavelength-division-multiplexing) technology is now the prevalent standard technology in optical communication. Being key components in performing wavelength selection and monitoring, as well as fast reconfiguration of optical networks, tunable optical filters have obtained rapid development in recent years. Various tunable technologies have emerged, such as MEMS technology[1], liquid crystal filter based on electro-optic effect[2], acousto-optic technology[3]. However, challenges in long-term reliability due to movable part or problems of polarization sensibility, prevent them from further commercialization.

As a robust, industry viable alternative, a silicon-based thermo-optic tunable optical filter is chosen. A crystalline silicon cavity thermo-optic filter was fabricated by our group[4], achieving a tuning range of 23nm, however the narrow FSR (free spectral range) of 7.2nm and complex fabrication process of wafer bonding limit its application. Grown at high tempera-

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ture and complex fabrication of multiple growth of DBR (distributed Bragg reflectors), the tuning range of polycrystalline silicon cavity is reported to be 5.3nm, which is limited by Peltier heater control range[5]. To simplify the fabrication process, we use amorphous-silicon cavity grown at low temperature, and acquire wide tuning range and potential low power consumption by using short cavity. In this paper, the fabrication of the filter is described first, followed by the test and analysis of its tunability.

2 Fabrication

The schematic of cross-section of Si-based thermo-optic tunable filter is shown in Fig. 1. Starting material is an n-type ⟨100⟩ double-polished silicon substrate, with resistance of 4~6Ω·cm. After boron implantation and rapid thermal annealing, p^{++} layer is formed as the heater. The purpose of using flat structure is to better control the thickness of later deposited layers and easier integration with other vertical structures, such as RCE (resonant-cavity-enhanced) photodetector. 3.5 pairs and 3 pairs of $\lambda/4$ Si/SiO_2 are grown subsequently by electron beam evaporation to form bottom and top DBR with high reflectivity. The center wavelength is about 1550nm, and the mirrors have high reflectivity over 95% in the band of 1200~1800nm. The cavity consists of a-Si layers between top and bottom DBR, with the optical length of $\lambda/2$. A 220nm thick silicon nitride layer is then deposited by PECVD (plasma-enhanced chemical vapor deposition) on the bottom of the substrate as AR (anti-reflection) coating, to eliminate the influence of silicon substrate on transmission spectrum of

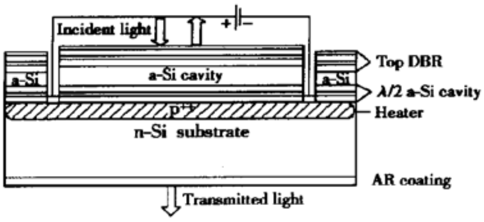

Fig. 1 Schematic of cross-section of Si-based thermo-optic tunable filter

the filter. After dry etching of patterned DBR, contact holes are made through the DBR layers to have electric access to the heater.

3 Results and discussion

Light from Agilent 8163A 1.55μm tunable laser (tuning range: 1510~1640nm) is adjusted to normally incident on the filter, an optical measurement system of Agilent 8164A detects the transmitted light from the filter, which is focused by lens and collimator. A DC voltage is applied to the heater resistor to supply heating power.

The simulated and measured transmission spectra of F-P filter are shown in Fig. 2. The larger FWHM of 9nm than calculated 3nm is mainly caused by mirror undulation[6] (i.e. large roughness and non-parallelism) and further absorption by the coating layers. Heating the filter increases the optical thickness of the cavity through an increase in the refractive index. The transmission peak thus shifts to longer wavelength as applied voltage increases, as shown in Fig. 3. The peak wavelength shifts from 1567.5nm at zero bias to 1579.5nm at 9V.

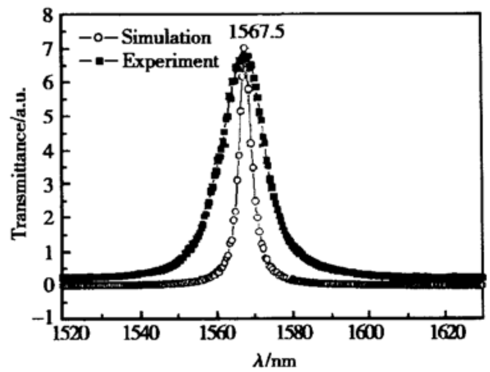

Fig. 2 Measured and simulated transmission spectra of F-P filter

Figure 4 summarizes the current, peak shift, and normalized peak integration intensity dependence on applied voltage, respectively. The current has good linear relation with the voltage, indicating stable resistance property of p^{++} heater. The peak shift increases with applied voltage, and the relationship is non-linear. A tuning range of 12nm has been achieved under

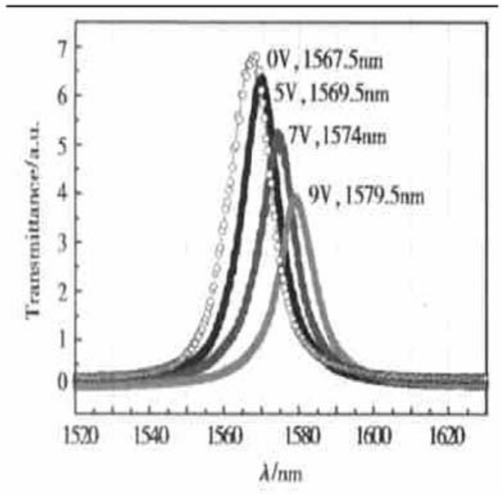

Fig. 3 Peak shift dependence on applied voltage of tunable F-P filter

9V. It is observed that the normalized peak integration intensity decreases to 60% of the initial value at 9V. The significant decrease is possibly due to the increase of intrinsic carrier absorption of the silicon substrate as the temperature increasing when tuning. The peak shift as a function of the heating power consumption is shown in Fig. 5. It is shown that there is a nearly perfect linear relationship between the peak shift and the heating power. The average tuning efficiency (S) is 0.0089nm/mW, or 8.9nm/W, and the average heating consumption (i.e. average power consumption needed to obtain 1nm tuning) is $1/S$ = 112.36mW/nm.

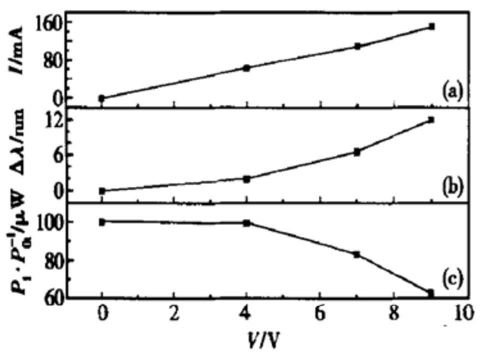

Fig. 4 Current (a), peak shift (b), normalized integrated intensity (c) of the peak versus applied voltage

Since the temperature change is the real force pushing the peak red shift, the thermal tuning mechanism is further investigated below. The thermo-optic

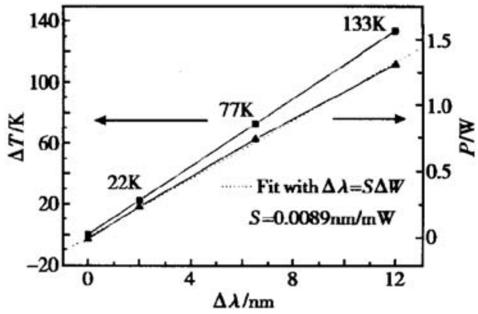

Fig. 5 Temperature and heat power versus peak shift

tuning of the F-P filter is governed by the effective thermo-optic coefficient[7].

$$\alpha_{eff} = \alpha_L + \frac{\alpha}{n} \tag{1}$$

where α_L stands for the coefficient of thermal expansion, α for thermo-optic coefficient, and n for the effective refractive index which is assumed to be 3.5 of a-Si at 1550nm.

Assuming DBR remains unchanged, the peak shift as a function of temperature can be expressed as:

$$\frac{d\lambda}{dT} = \alpha_{eff}\lambda \tag{2}$$

Since the equivalent peak shift is wavelength dependent, the spectrum is slightly distorted when the filter is thermo-optically tuned. Considering that α of a-Si is 2×10^{-4}/K[8], α_L is 2.6×10^{-6}[9], n is 3.5, α_{eff} is 5.97×10^{-5}/K,

$$\frac{\Delta\lambda}{\Delta T} = 0.0938\text{nm/K}(\lambda = 1570\text{nm}) \tag{3}$$

According to equation (3), the peak shift is only determined by temperature changing, and their relationship is shown in Fig. 5. Taking the value of S, the heating efficiency can be obtained to be around 0.1K/mW, which means the temperature of the cavity will increase 0.1K when supplying 1mW power. The heating efficiency of a polycrystalline silicon filter with a 500μm diameter size, optical length of the cavity $\lambda/2$ and a directly heating structure, has been calculated in literature[5] to be 13.6K/mW. The two order of magnitude discrepancy indicates some mechanisms do exist to deplete tremendous energy. Two factors must be considered. Firstly the good thermal conductivity of silicon substrate makes it a heat sink, from which major heat transfer to the environment. Secondly, the energy loss storing in the bottom DBR also contributes to the decrease of heating efficiency.

The previous calculation assumes that DBR remains unchanged when temperature changes. However, since the refractive index as well as the physical thickness of each layer will increase when temperature changes, which will affect the optical property of DBR, the influence of temperature-induced DBR reflection band change on peak shift should be taken into account. As the top DBR can hardly be influenced by temperature change, only the optical behavior of bottom DBR will be investigated. The bottom DBR is similar to a modulated grating, in which the optical length of the layer changes gradually according to its distance to the heater. Since the signs of coefficients of thermo-optic and thermal expansion are both positive for a-Si and SiO_2, it means the optical length of the layer nearest to the heater has the largest change, while that of the layer far away from the heater can remain unchanged.

The thermo-optic coefficient α of SiO_2 is $1\times10^{-5}/K$[10], thermal expansion coefficient α_L of SiO_2 is 0.5×10^{-6}[9], α of a-Si is $2\times10^{-4}/K$[8], α_L is 2.6×10^{-6}[9]. Considering thermal conductivity of a-Si is similar to SiO_2, we assume the temperature distribution of the layers of the bottom DBR (i.e. SiO_2/Si/SiO_2/Si/SiO_2) obeys linear relationship. Since the thickness of SiO_2 is roughly twice of a-Si, the temperature gradient of each layer can be assumed as $1.5\Delta T$, $1.75\Delta T$, $2.25\Delta T$, $2.5\Delta T$, $3\Delta T$, respectively. The reflection behavior of the bottom DBR can be determined by transferring matrix method (details in literature[11]), when ΔT is 50, 100, and 150K, respectively. The reflection band shifts toward longer wavelength slightly when ΔT increases, as shown in Fig. 6. The reflection increases no more than 0.5% in the range of 1510~1640nm. Figure 7 indicates that the peak shifts 1nm when ΔT is 50K, and 2nm when ΔT is 150K, if we just consider the influence of temperature on bottom DBR and ignore its effect on the cavity. Taking 50K and 150K of ΔT into equation (3), peak shift caused by the temperature change of the cavity is 5nm and 14nm, respectively. Comparing the peak shift values, it is evident that a fraction of peak shift is due to the temperature effect on the reflection band change, and the peak shift induced by reflection band change accounts for about 10%~20% of the whole peak shift.

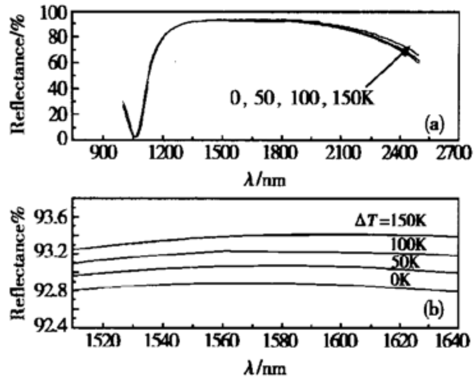

Fig. 6 Reflectance versus wavelength (a) Reflection spectrum of the whole band; (b) Reflection spectrum of 1510~1640nm

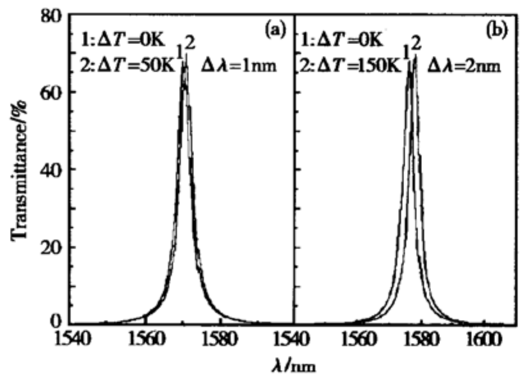

Fig. 7 Peak shift induced by red-shift of the reflection band of bottom DBR

4 Conclusions

A 1.55μm thermo-optic Si-based filter with large tuning range is realized. Owing to the advantage of simple fabrication process, high compatibility, it can be easily integrated with RCE photodetector to fabricate tunable detector. The tuning range is 12nm, and FWHM is 9nm. The bandwidth can be reduced greatly by controlling the growth of DBR, and the heating efficiency can be increased by improving the filter structure in the future work.

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1.55μm 非晶硅热光 F-P 腔可调谐滤波器*

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摘要: 介绍了一种 Si 基热光 Fabry-Perot (F-P) 腔可调谐滤波器. F-P 腔由电子束蒸发的非晶硅构成. 利用非晶硅的热光效应, 通过对 Si 腔加热, 改变 F-P 腔的折射率, 从而引起透射峰位的红移. 该原型器件调谐范围为 12nm, 透射峰的 FWHM(峰值半高宽) 为 9nm, 加热效率约为 0.1K/mW. 精确控制 DBR(分布式 Bragg 反射镜) 生长获得高反射率镜面是减小带宽的有效途径; 通过改进加热器所处位置及增强散热能力, 有望进一步提高加热效率.

关键词: 热光效应; Fabry-Perot; 可调谐滤波器; 非晶硅
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