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 range 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.

Keywords: thermo-optical effect; Fabry-Perot; tunable filter; a-Si

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, liquid crystal filter based on electro-optic effect, acousto-optic technology. 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, 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 temperature and complex fabrication of multiple growth of DBR...
(distributed Bragg reflectors), the tuning range of polycrystalline silicon cavity is reported to be 5.3 nm, 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 λ/4 Si/SiO₂ are grown subsequently by electron beam evaporation to form bottom and top DBR with high reflectivity. The center wavelength is about 1550 nm, and the mirrors have high reflectivity over 95% in the band of 1200~1800 nm. The cavity consists of a-Si layers between top and bottom DBR, with the optical length of λ/2. A 220 nm 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 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 1.55 μm tunable laser (tuning range: 1510~1640 nm) 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 9 nm than calculated 3 nm 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 1567.5 nm at zero bias to 1579.5 nm at 9 V.

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

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 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 $1/S = 112.36$ mW/nm.

Since the temperature change is the real force pushing the peak red shift, the thermal tuning mechanism is further investigated below. The thermo-optic tuning of the F-P filter is governed by the effective thermo-optic coefficient $a_{eff}$

$$a_{eff} = a_L + \frac{a}{n}$$

where $a_L$ stands for the coefficient of thermal expansion, $a$ 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:

$$\frac{d\lambda}{dT} = a_{eff} \lambda$$

Since the equivalent peak shift is wavelength dependent, the spectrum is slightly distorted when the filter is thermo-optically tuned. Considering that $a$ of a-Si is $2 \times 10^{-4}$/K, $a_L$ is $2.6 \times 10^{-6}$/K, and $n$ is 3.5, $a_{eff}$ is $5.97 \times 10^{-5}$/K,

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

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.
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 SiO₂, 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 $a$ of SiO₂ is $1 \times 10^{-5}/K^{[10]}$, thermal expansion coefficient $a_l$ of SiO₂ is $0.5 \times 10^{-6}[x]$, $a$ of a-Si is $2 \times 10^{-4}/K^{[x]}$, $a_l$ is $2.6 \times 10^{-6}[x]$. Considering thermal conductivity of a-Si is similar to SiO₂, we assume the temperature distribution of the layers of the bottom DBR (i.e. SiO₂/Si/SiO₂/Si/SiO₂) obeys linear relationship. Since the thickness of SiO₂ 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 $\Delta T$ is 50, 100, and 150K, respectively. The reflection band shifts toward longer wavelength slightly when $\Delta T$ 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 $\Delta T$ is 50K, and 2nm when $\Delta T$ 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 $\Delta T$ 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% to 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](a) 1: $\Delta T=0K$, $\Delta \lambda=1nm$ 2: $\Delta T=50K$, $\Delta \lambda=2nm$ (b) 1: $\Delta T=0K$, $\Delta \lambda=2nm$ 2: $\Delta T=150K$, $\Delta \lambda=14nm$

### 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 12 nm, and FWHM is 9 nm. 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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