Ultra compact triplexing filters based on SOI nanowire AWGs*

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Abstract: An ultra compact triplexing filter was designed based on a silicon on insulator (SOI) nanowire arrayed waveguide grating (AWG) for fiber-to-the-home FTTH. The simulation results revealed that the design performed well in the sense of having a good triplexing function. The designed SOI nanowire AWGs were fabricated using ultraviolet lithography and induced coupler plasma etching. The experimental results showed that the crosstalk was less than –15 dB, and the 3 dB-bandwidth was 11.04 nm. The peak wavelength output from ports a, c, and b were 1455, 1510 and 1300 nm, respectively, which deviated from our original expectations. The deviation of the wavelength is mainly caused by 45 nm width deviation of the arrayed waveguides during the course of the fabrication process and partly caused by material dispersion.

Key words: triplexer; FTTH; nanowire; AWG; wavelength division multiplexing (WDM)

DOI: 10.1088/1674-4926/32/4/044009 **EEACC:** 4140

1. Introduction

With the rapid increase in bandwidth requirement, the speed in accessing networks becomes a bottleneck. FTTH, which has recently been developed significantly, holds some promise. Among all of the elements in FTTH applications, the cost reduction of the optical network unit (ONU) takes the key role. The ONU consists of a triplexing filter for an optical wavelength division multiplexing function, a laser diode (LD) and photodiodes (PDs).

According to the ITU-T 984 standard, the triplexing filter of the ONU module transmits 1310 nm upload data, and receives 1490 nm download data and 1550 nm download analog signals. The most common triplexing filter is the thin film filter (TFF) embedded in a planar lightwave circuit (PLC) platform, and the embedded TFFs set up a very complicated assemblage requirement. Triplexing filters based on a planar waveguide which can be used for hybrid integrating with LD and PDs conveniently seems to be promising[1]. Among these devices, silica arrayed waveguide gratings have been researched recently[2–5]. However, these kind of filters are of large dimensions, which are only hybrid integrated with LD and PDs. This gave us the idea that the recently developed silicon on insulator nanowire platform could be an alternative[6,7].

Due to very high index contrast (40%) and compatibility with CMOS fabrication technology, SOI nanowire devices are usually of very small dimensions and could be integrated with LD, PD and transimpedance amplifiers (TIAs) easily. There are a number of wavelength demultiplexer designs, such as devices based on ring resonators, cascaded Mach–Zehnder interferometers, arrayed waveguide gratings and echelle grating devices. The responses of arrayed waveguide gratings and echelle gratings are not so sensitive to local process variations as those of ring resonators and cascaded Mach–Zehnder devices. However, insert losses of echelle grating devices reported to date are higher than the AWGs, and grating profile imperfections and the verticality of etched grating facets remain a critical issue[8, 9]. In this paper, we present an ultracompact triplexing filter based on SOI nanowire AWGs. This proposed ultracompact triplexing filter is easily monolithically integrated with a 10 Gbps Ge/Si waveguide photodiode and evanescent laser[10, 11], and it can be used in a 10 gigabit Ethernet passive optical network (GEPON) ONU in future FTTH. As far as we know, this is one of the smallest triplexing filters that has been fabricated so far.

2. Design of SOI flattop AWG triplexers

In order to ensure a TE single mode condition, the width of the waveguide was set to 500 nm and the thickness was set to 220 nm. Because of the wide wavelength space from 1310 to 1550 nm, the three wavelengths of triplexing filter did not operate at the same diffraction order[2, 3]. We designed three wavelengths (1310, 1490 and 1550 nm) operated at two different diffraction orders. Wavelengths of 1490 and 1550 nm operated at the m diffraction order, and the wavelength of 1310 nm operated at the $m+2$ diffraction order. The central wavelengths of the AWGs are 1520 and 1310 nm, respectively. As can be seen in Fig. 1, the wavelengths of 1490 and 1550 nm output from ports a and c, respectively, and the wavelength of 1310 nm input at port b. The central wavelengths of those selected two diffraction orders satisfy the following equations,

* Project supported by the National High Technology Research and Development of China (No. 2006AA03Z420), the National Natural Science Foundation of China (Nos. 60776057, 60837001, 60776057) and the State Key Laboratory on Integrated Optoelectronics Project, China (No. 2010KFB005).

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Received 28 September 2010, revised manuscript received 9 November 2010

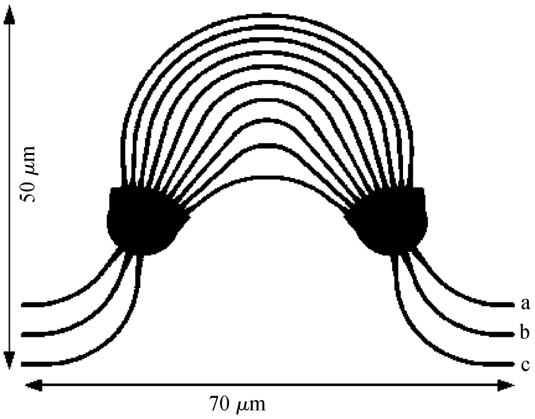

Fig. 1. Schematic of a triplexer based on silicon nanowire flattop AWGs.

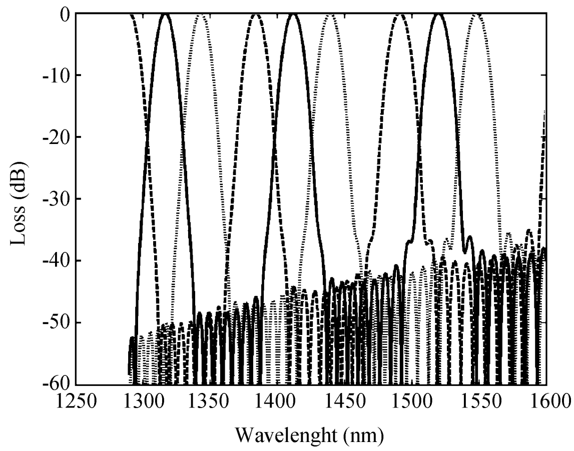

Fig. 2. Simulated transmission spectra of SOI nanowire AWG.

Table 1. Design parameters of AWGs for triplexers.

Parameter	Value
Diffraction order m	8
Length difference of adjacent waveguides	4.91 μm
Length of free propagation region (FPR)	9.24 μm
I/O waveguide space	1.3 μm

$$n_c(1310\,\text{nm})\Delta L = (m+2)\cdot\lambda(1310\,\text{nm}), \quad (1)$$

$$n_c(1520\,\text{nm})\Delta L = m\cdot\lambda(1520\,\text{nm}), \quad (2)$$

where λ is the central wavelength, n_c is the effective refractive index of the arrayed waveguide, ΔL is the optical path length difference of adjacent arrayed waveguides, and m is the order of diffraction. The pitch of arrayed waveguides was $d = 1\ \mu$m. To obtain the smooth mode conversion, linear tapers of 1 μm width and 3 μm length were inserted between the I/O waveguides and slab waveguides. To reduce the connection loss between arrayed waveguides and slab waveguides, linear tapers of 0.8 μm width and 1.3 μm length were also inserted. The channel spacing $\Delta\lambda$ was expected to be 30 nm and the number of arrayed waveguides N was 10. The other parameters are listed in Table 1. The chip size, as shown in Fig. 1, is only $70 \times 50\ \mu\text{m}^2$, which is much smaller than that of other AWG triplexing filters[2, 3].

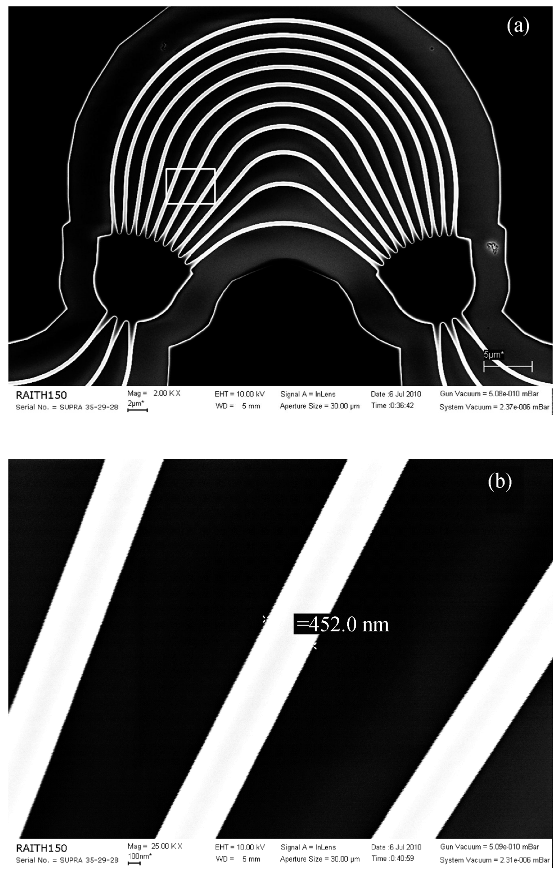

Fig. 3. SEM of the fabricated AWG. (a) Top view. (b) Enlarged view of the white square.

3. Simulation and test results

The transmission spectra simulated by a simple transmission function method are shown in Fig. 2, where spectral responses from ports a, b, and c corresponded to dashed, solid, and dotted lines, respectively. One can see that the peak wavelengths output from ports a, c, and b were 1490, 1550 and 1310 nm, respectively, which agreed well with our design. The adjacent channel crosstalk was less than –50 dB and the device had a good triplexing function.

The designed SOI nanowire AWGs were fabricated using ultraviolet (193 nm) lithography and induced coupler plasma (ICP) etching. The etching SEM photograph is shown in Fig. 3(a), and Figure 3(b) is the enlarged view of the white square. The width of the waveguides measured through SEM is about 452.0 nm, which is 48 nm narrower than that we designed. A 750 nm-thick silica film was deposited after ICP etching. The end faces of the AWGs were polished after being diced from the wafer.

The ultra-wideband TE optical source with a wavelength range from 1000 to 2000 nm (Santec UWS-1000), which was obtained by an in-line polarizer, was coupled into the input waveguide. The output optical spectra were tested by an AQ6370B spectrometer. The transmission spectra for the TE-polarization signal are shown in Fig. 4 as solid lines (coupling

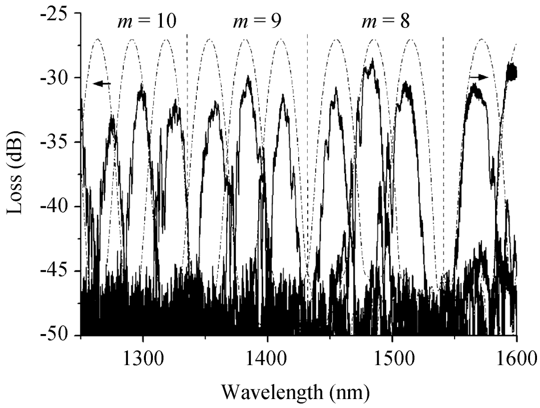

Fig. 4. Transmission spectra of SOI nanowire AWGs. The measured and simulated data correspond to the solid and dashed lines, respectively.

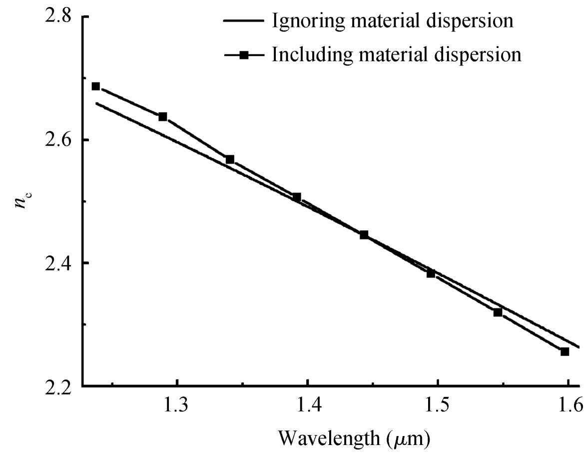

Fig. 5. Dependence of the effective refractive index n_c and with different wavelengths.

losses from/to fibers were included). The peak wavelengths from ports a, c, and b are 1455, 1510 and 1300 nm, respectively, which deviated from the original expectations. The deviations were mainly caused by the width deviation of the arrayed waveguides. For $m = 8$, the measured central wavelength λ_0 is about 1486 nm, then we can get the $n_c \approx 2.42$ from Eq. (2). As the effective refractive index was $n_c \approx 2.42$, the width of the waveguide is about 455 nm for a 220 nm-thick SOI, which was in accordance with the width measured by SEM.

The width of arrayed waveguides was changed to 455 nm and the transmission responses were re-calculated and shown in Fig. 4 as dashed lines. The simulated responses were reshaped for comparison purposes. The λ_0, $\Delta\lambda$ and FSR decreased as the width of the arrayed waveguides narrowed. The contrast between measurements and simulations illustrated that the simulation results were in accordance with the measurements. The deviations in the output wavelengths were mainly caused by the width deviation of the arrayed waveguides during the course of the fabrication process.

Compared with the simulation results, the measured data showed that the 1300 nm wavelength shifted towards the long wavelength direction but the 1510 nm wavelength shifted towards the short wavelength direction. This was mainly caused by material dispersion. The central wavelength increased with the effective refractive index n_c, as described in Eq. (1). The refractive index of silicon decreased with increasing wavelength. In the simulation, the refractive index was a constant. It was less than the actual value around 1300 nm and greater than the actual value around 1510 nm, the same for the effective refractive index n_c, as shown in Fig. 5. So compared with the simulation results, the measured peak wavelengths ranged from 1300 to 1400 nm shifted towards the long wavelength direction and peak wavelengths ranged from 1510 to 1600 nm shifted towards the short wavelength direction. Considering material dispersion, the simulated peak wavelengths are in accordance with the measurements, as shown in Fig. 6.

The crosstalk between adjacent channels was about –15 dB and the 3-dB-bandwidth was 11.04 nm. The large crosstalk was mainly due to the phase errors resulting from the width fluctuations of the arrayed waveguides. The insert loss is about –30 dB, including coupling losses from/to fiber at both sides.

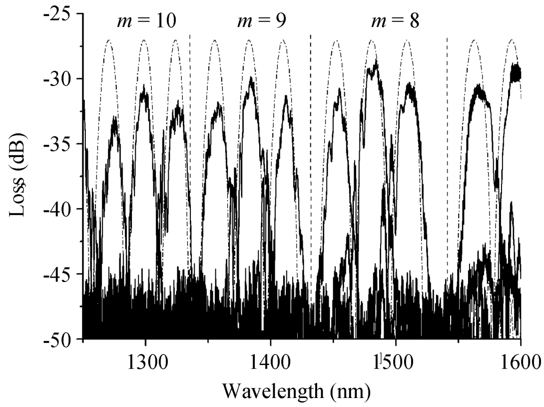

Fig. 6. Transmission spectra considering material dispersion. The measured and simulated data correspond to solid and dashed lines, respectively.

The coupling loss is estimated to be –22 dB estimated by the fiber-chip-fiber loss for a straight waveguide, and the in-chip loss of the AWG is about –8 dB. The high in-chip loss is mainly due to the propagation loss of the input and output waveguide and the large scattering loss of the nanowire waveguide. The crosstalk and insert loss can be reduced by optimizing the fabrication process.

4. Conclusions

In conclusion, a $70 \times 50\ \mu m^2$ triplexing filter based on SOI nanowire AWGs was designed and fabricated. This is one of the smallest triplexing filters that has been fabricated so far. Simulation results showed that the designed device had a good triplexing function. Experimental results showed that the peak wavelengths output from ports a, c, and b are 1455, 1510 and 1300 nm, respectively. The adjacent channel crosstalk is less than –15 dB and the 3-dB-bandwidth is 11.04 nm. Because the average width of the arrayed waveguides was reduced by 45 nm during the course of the fabrication process, the peak wavelengths deviated from our original expectations. And the deviation was partly caused by material dispersion. If material dispersion was considered and the effective refractive index n_c

was calculated accurately, and also the width of the fabricated arrayed waveguide was as precise as the design, the chip could be expected to provide good triplexing performance.

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