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Light Pipe Array as Coupling Adaptor between Fiber Array and Free-Space Wavelength Division Demultiplexer

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A light pipe array (LPA) is proposed as a coupling adaptor between a commercial fiber array and a free-space dense wavelength division demultiplexer (free-space DWDDM). The LPA has been fabricated on a silicon-on-insulator wafer using the semiconductor fabrication technology and coated with a thermal oxidation layer on its input and output surfaces as an anti-reflection film. In the experiment, the free-space DWDDM system with the LPA has been demonstrated with an insertion loss of 2.4 dB and an adjacent cross-talk of −17 dB. [DOI: 10.1143/JJAP.46.5456]

KEYWORDS: coupling adaptor, free-space dense wavelength division demultiplexer (DWDDM), anti-reflection film

1. Introduction

A free-space dense wavelength division demultiplexer (free-space DWDDM) is attractive for optical networks usage because it is capable of processing an optical signal in a parallel manner.[1–7] Although other DWDDM devices such as arrayed waveguide gratings (AWGs) have high-channel capacity by parallel processing, they usually have some problems in terms of high insertion loss, high polarization sensitivity, small free-spectral range, and lack of thermal stabilization. In contrast, due to the our proposal free-space configuration using grism structure as wavelength demutiplexing device, free-space DWDDM can prevent or ease the above problems and maintain the merit or parallel processing.[7] In spite of the free-space demultiplexer having the advantage of high efficiency, for a commercial fiber array, to receive the output signal from this free-space DWDDM efficiently is still a problem. The main reason for the coupling loss is due to the mismatch between the core spacing of a commercial fiber array and the channel spacing of the demultiplexer.[3,7] Thus, to realize efficient coupling, an adaptor between the free-space DWDDM and the fiber array is necessary. Since a light pipe array (LPA) is utilized as an adaptor to enhance the coupling efficiency of free-space DWDDM, it contributes to the realization of a DWDDM with a low coupling loss, high channel capacity, and rapid processing rate. However, there are few attempts at present to realize such a coupling adaptor. Therefore, a LPA is proposed as a coupling adaptor to improve coupling efficiency. In this paper, the design, fabrication, and measurement of the LPA are presented for the first time. The optical properties of the package system consisting of the free-space DWDDM, LPA, and a multimode fiber array are also discussed.

2. Design and Fabrication

A free-space DWDDM system with the proposed coupling adaptor is shown in Fig. 1. The system employing the blazed grism with the grating pitch of 20 mm has sixteen channels with a wavelength spacing of 0.8 nm in the C band from 1545.2 to 1557.2 nm. According to the reported free-space DWDDM,[7] the diameter of the output field is about 24 μm, which is threefold larger than that of a single-mode fiber. To fit a receiving single-mode fiber, although a focal lens with a larger numerical aperture (NA) can decrease the output field diameter of this demultiplexer, such a lens requires sufficient high quality with very few aberrations, which will increase the cost and decrease the tolerance of the whole free-space DWDDM system. Therefore, a multimode LPA is proposed in this study.

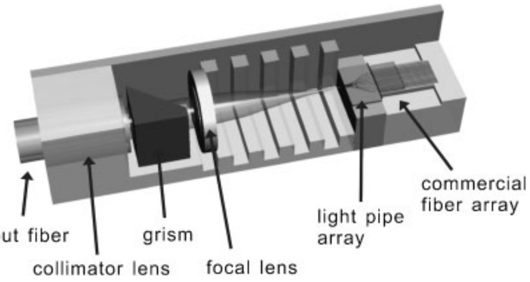

Fig. 1. Schematic diagram of free-space DWDDM system.

To design a LPA, the spacing between adjacent light pipes at the input port must match the spot separation (36.27 μm) of the output field of the reported free-space DWDDM.[7] At the output port of LPA, the spacing between the adjacent light pipes has to fit the core spacing (250 μm) between the adjacent channels of a commercial fiber array. As shown in Figs. 2(a) and 2(c), the cross-sections of the light pipes are rectangular, whereas the height and width are 34 and 31 μm, respectively. The detail specifications of the designed LPA are shown in Fig. 2. There are two reasons for choosing a silicon material as the light pipes. One is that silicon has a high refractive index and a high transmittance in the C band, which can bring high efficiency for the light guide. The other reason is that silicon is a commonly available material in standard semiconductor processes.

The LPA consists of sixteen light pipes with different bends. Every light pipe is constructed as an S band with two opposite bending directions but the same bending radius. The properties of the LPA are calculated using BeamPROP™ software. The curve of the bending loss shown in Fig. 3 is a function of the bending radius. In this figure, the first and final channels possess the smallest bending radius of 5 mm and the maximum bending loss of

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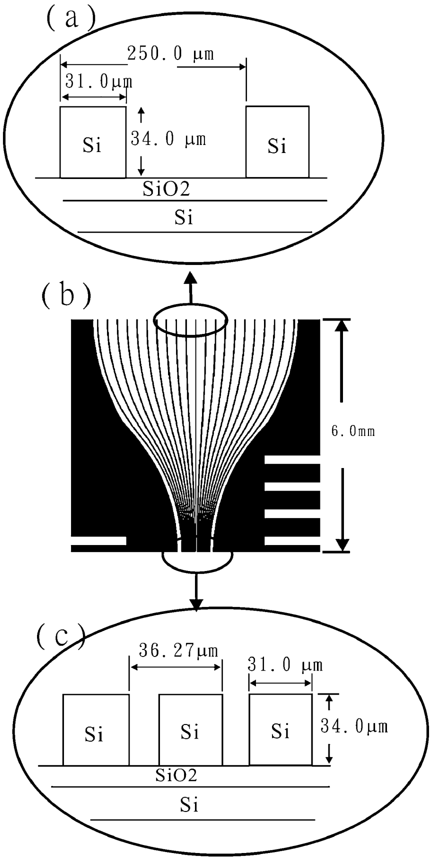

Fig. 2. Specification of designed LPA. (a) Cross-section in output port; (b) top view; (c) cross-section in input port.

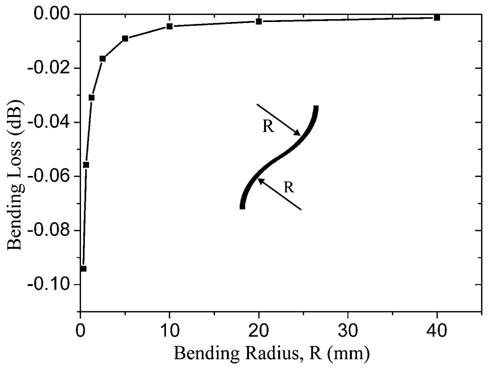

Fig. 3. Bending loss as a function of bending radius.

0.009 dB in the simulation. The propagation loss of a silicon light pipe is mainly due to the unevenness and roughness of the sidewall resulting from lithography and etching.[8,9)]

The LPA was fabricated by the standard optical lithography and inductively coupled plasma-reactive-ion etching (ICP-RIE). Figure 4 shows the scanning electron microscopy (SEM) photographs of the fabricated pipes at the input and output ports. The average roughness of the pipe sidewall was around 10.5 nm by atomic force microscopy (AFM); such sidewalls with less roughness can reduce the propagation loss. To reduce the Fresnel-reflection loss of the high-refractive index material (silicon), the anti-reflective (AR) coating produced by thermal oxidation, instead of evaporation or sputtering technologies, was treated on the input and output surfaces of the light pipes in the final fabrication. The etched light pipe array was placed in the furnace, and the furnace temperature was slowly increased from room temperature to the oxidation temperature. In this process, we have to avoid the warping of the light pipes due to the rapid temperature change. The temperature variation curve of the furnace is shown in Fig. 5. All the oxidation processes were carried out at 1050 °C. Oxidation time in this paper refers to the period from the switching on of the reaction gases, i.e., oxygen and hydrogen, to the switching off of these gases. Before and after the oxidation time, nitrogen gas was supplied to stop oxidization. When we finished the oxidizing process, natural cooling was needed. We placed the LPA out of the furnace until it reached room temperature. The thickness of the silica layer is shown in Fig. 6 as a function of oxidation time. For comparison, samples with different thicknesses of silica are fabricated, as shown in Fig. 7. The refractive index of the silica layer measured using an ellipsometer (SOPRA GES5) is 1.444 at a wavelength of 1550.8 nm. Although the refractive index of the AR material used in this fabrication is not the optimum value of 1.85, the silica layer could efficiently reduce the interface reflection loss of silicon from 51.4 to 9.75% in the simulation. In the consideration of mass AR-coating, the silica layer can play the role of the AR layer using the oxidation furnace system.

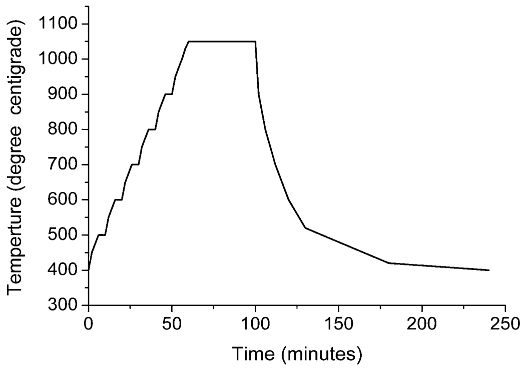

Fig. 5. Temperature variation curve of furnace.

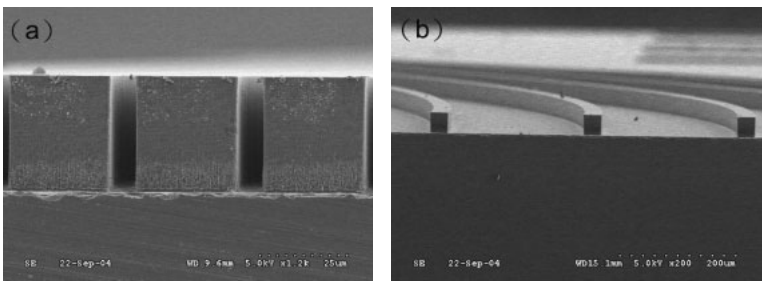

Fig. 4. Scanning electron microscopy photographs of etched pipes in part (a) for input port and (b) for output port.

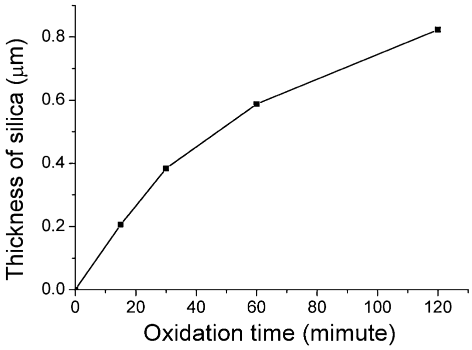

Fig. 6. Thickness of silica layer as a function of oxidation time.

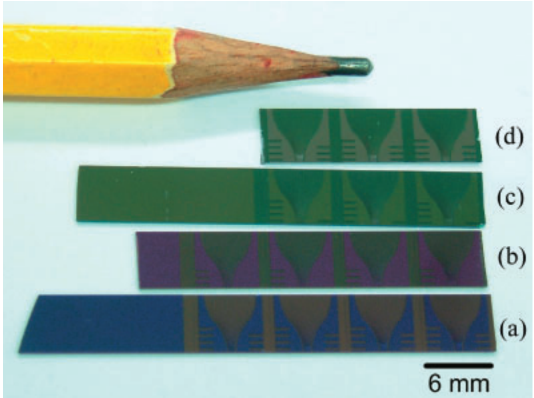

Fig. 7. Fabricated LPA with different thicknesses of AR layer. (a) 0.269, (b) 0.476, (c) 0.589, and (d) 0.0 μm.

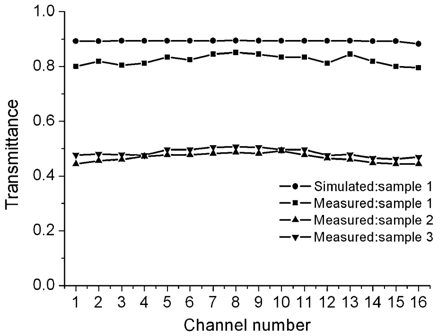

Fig. 9. Transmittance of LPA for the samples with different thicknesses of silica layer. Sample 1: 0.269 μm; sample 2: 0.589 μm; and sample 3: 0.0 μm.

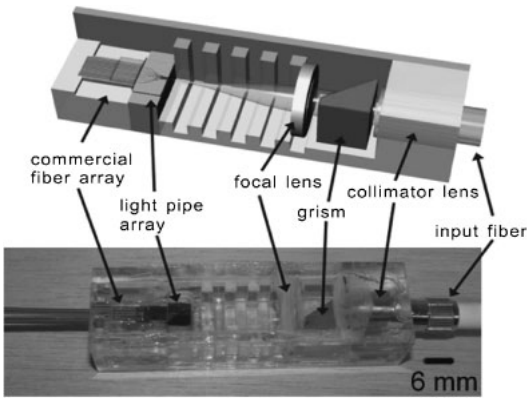

Fig. 10. Packaged demultiplexer system composed of (a) transmission fiber, (b) collimator lens, (c) grism, (d) focal lens, (e) light pipe array, and (f) fiber array.

3. Measurement

We measured the intensity distribution of each channel of the fabricated LPA. The experimental setup is illustrated in Fig. 8. The optical source with a spectral width of 0.2 nm was provided by a tunable laser source (Anritsu MG9541A). An IR detector was placed behind the LPA to record the output intensity distributions at the central wavelength of each channel. The insertion losses of the LPA samples with different thicknesses of the silica layers are measured and compared, as shown in Fig. 9. In this figure, the insertion loss of sample 1 with a quarter-wave layer of silica is improved efficiently. To verify the function of the fabricated LPA in a free-space DWDDM system, we packaged this component with the prefabricated free-space DWDDM and a commercial multimode fiber array to form a complete demultiplexer system, as shown in Fig. 10. The output fiber array is a commercial multimode fiber with a core diameter of 50 μm and an adjacent spacing of 250 μm. Then, the optical performance of the packaged system was measured. Figure 11 shows the measured transmission spectra of this system with a 100 GHz channel spacing in the wavelength range from 1544.0 to 1559.0 nm. The measured 3 dB bandwidth of each channel is within 0.62 nm. The bandwidth is narrower than those reported in other literatures[3)] without any coupling adaptor. Thus, the coupling adaptor can increase the channel spacing of a free-space DWDDM system. From our experiment, the next-neighbor cross-talk is lower than −17 dB, and the average loss including the reflection loss of each device is 2.4 dB. The main loss comes from the reflectance of grism (1.74 dB), and can be reduced by AR coating on its surface.

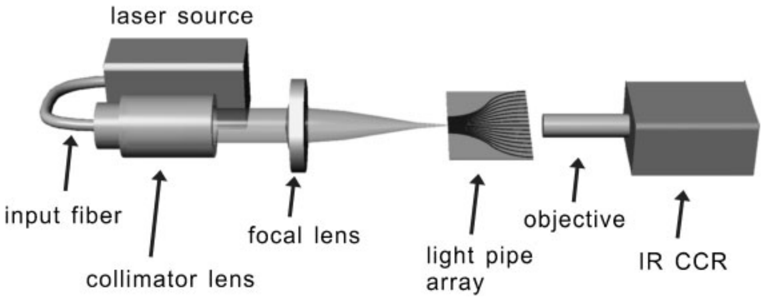

Fig. 8. Experimental setup for measuring the properties of LPA.

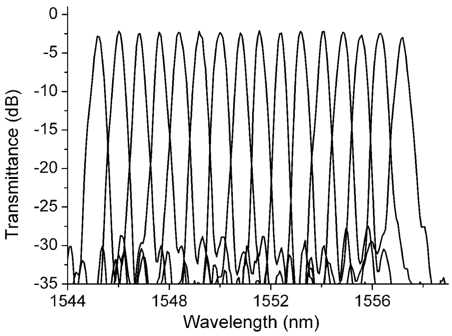

Fig. 11. Measured transmission spectra of packaged system form 1544.0 to 1559.0 nm.

4. Conclusions

A LPA has been proposed as a coupling adaptor to connect the free-space DWDDM to a commercial fiber array. The LPA with an AR film has been fabricated using photolithography, ICP-RIE, and thermal oxidation. The investigation shows that a very simple oxidation process can be used to form an AR layer on a silicon base element that reduces the insertion loss of the coupling adaptor. The experimental results have demonstrated that a free-space demultiplexer system with the proposed LPA as a coupling adaptor can narrow down the bandwidth of a free-space DWDDM system efficiently. With the proposed LPA component, the cross-talk of the free-space DWDDM can be less than −17 dB. Therefore, the LPA has provided a solution to the light coupling between a free-space DWDDM and a commercial fiber array.

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