Silica-based Arrayed-waveguide Gratings for the Visible Wavelength Range

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Abstract

We describe silica-based arrayed-waveguide gratings (AWGs) that operate in the visible wavelength range. By optimizing the waveguide parameters, we obtained a small propagation loss of 0.4 dB/cm in this wavelength range. We designed and fabricated an AWG with a rainbow-like output covering the range from 400 to 700 nm and an AWG with a narrow output wavelength spacing of 0.75 nm and a center wavelength of 700 nm. Both AWGs have excellent spectroscopic characteristics, proving that the application range of silica-based AWGs can be expanded.

1. Introduction

The use of waveguide division multiplexing systems is increasing rapidly and, in these systems, arrayed-waveguide gratings (AWGs) play important roles as multiplexer/demultiplexers [1]-[3]. They offer compactness, high stability, excellent optical characteristics, and mass producibility. Until now, AWGs have been developed solely for telecommunication applications, so their wavelength range has been limited to 1.3–1.6 µm [4]. However, for novel applications such as sensors [5], [6], we need AWGs with a shorter wavelength range, including the visible wavelength range. This is because many materials and analytes have specific characteristics at these wavelengths. Until now, only theoretical consideration has been given to AWGs operating in the visible wavelength range [7].

One of the key advantages of AWGs is their ability to provide the fine wavelength resolution required for optical spectroscopic sensors designed to identify materials and analytes [6]. This arises from the design flexibility of the waveguide layout and enables us to obtain arbitrary spectroscopic characteristics by changing the path length difference between neighboring arrayed waveguides and the focal length of the slab waveguides.

This paper describes the first experimental results obtained for silica-based AWGs that operate in the visible wavelength range. It shows that silica-based visible AWGs have the potential for application to the field of spectroscopy as well as to short-wavelength optical communication systems [8].

2. Design

The configuration of an N × N AWG multiplexer is shown in **Fig. 1**. The multiplexer consists of N input/output waveguides, two focusing slab waveguides, and arrayed waveguides with a constant path length difference ΔL between neighbors. Multiwavelength light input to one of the input waveguides is launched into the first slab waveguide and excites the arrayed waveguides. After traveling through the arrayed waveguides, the light beam interferes constructively at one focal point in the second slab. The location of the focal point depends on the signal wavelength λ because the relative phase delay in each waveguide is given by ΔL/λ. The slab and arrayed waveguides act as a lens and a diffraction grating,

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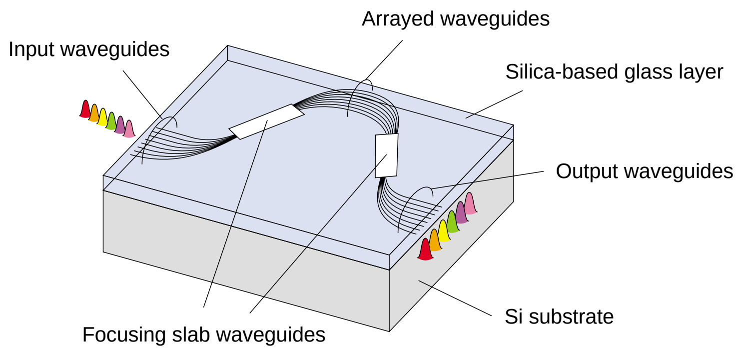


Fig. 1. Schematic configuration of silica-based arrayed-waveguide grating.

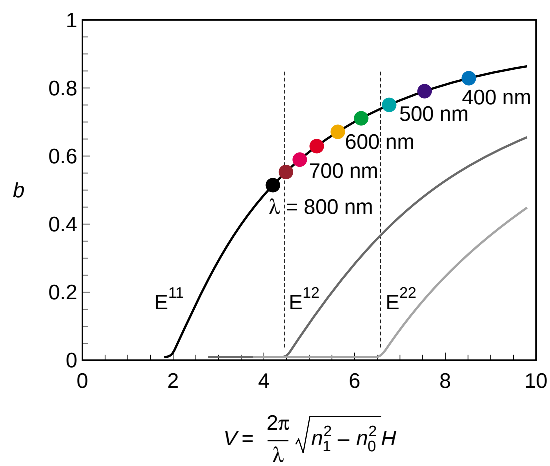
respectively.

First, we optimized a set of waveguide parameters for the visible wavelength range. A wide waveguide generally has a low propagation loss because the scattering caused by the sidewall roughness of the waveguide has a less severe effect. Moreover, the radiation loss at the bent waveguides is also reduced. On the other hand, the use of wide waveguides that allow multiple modes has a detrimental effect on optical characteristics such as modal noise. A quasi-single-mode waveguide with a slightly larger waveguide width than a true single-mode waveguide can provide both low loss and low modal noise. To achieve a quasi-single-mode condition, we evaluated the dispersion characteristics of a quasi-single-mode waveguide in the visible wavelength range. The dispersion characteristics of a waveguide are expressed by the relation between the normalized frequency V and the normalized propagation constant b, which is given by

$$V = \frac{1}{\sqrt{1-b}}\left(\arctan\sqrt{\frac{b}{1-b}} + \frac{\pi}{2}m\right), \tag{1}$$

where m denotes the mode number. The relation provides the condition that governs how many modes can be allowed in the waveguide. **Figure 2** shows the calculated dispersion characteristics of waveguides with a refractive index contrast of 0.75% and a core size of 3 μm × 3 μm. The cutoff wavelengths for the E^{12} and E^{22} modes are 750 nm and 530 nm, respectively. In other words, a quasi-single-mode condition can be achieved between 530 and 750 nm with this set of waveguide parameters.

We designed an AWG that can resolve a very wide spectral range of 450 to 750 nm. It requires only a small diffraction order of one; therefore, we chose a gull-wing-shaped AWG layout to achieve sufficient separation between the arrayed waveguides by using S-shaped waveguides (as shown in the inset of **Fig. 5(a)**). The path length difference and the center transmission wavelength were 0.35 μm and 500 nm, respectively. The wide-range AWG was 26 mm × 5 mm in size. We designed another AWG that has a narrow output wavelength spacing of 0.75 nm and a high diffraction order of 105 with a long path length difference of 50.18 μm to investigate high-wavelength-resolution applications such as absorption spectrum analysis. The layout was similar to that of conventional AWGs designed for telecommunication use (see **Fig. 5(b)**). This AWG was 20 mm × 12 mm. The minimum bending radius was set to 4 mm for both AWGs.



n_1: refractive index of the cladding
n_0: refractive index of the core
H: hight of the waveguide

Fig. 2. Dispersion characteristics of silica-based waveguide for visible wavelength range.

3. Results

We fabricated the AWGs using conventional silica-based planar lightwave circuit (PLC) technology including flame hydrolysis deposition and reactive ion etching with the waveguide parameters described in the previous section. In the following experiments, a halogen lamp (Ando AQ4303B) was used as a light source. The light was launched into the waveguides through optical fibers designed to handle visible wavelengths. The output spectra of the waveguides were measured with an optical spectrum analyzer (Ando AQ6315A).

Figure 3 shows transmission spectra of a 20-mm-long straight waveguide and of a 28-mm-long curved waveguide with a bending radius of 4 mm. They were fabricated before the AWGs and enable us to investigate the waveguides themselves. The insertion losses of the waveguides at a wavelength of 630 nm were 1.3 and 1.6 dB, respectively. Assuming that the loss difference was caused only by waveguide propagation loss, the estimated propagation and fiber coupling losses were 0.4 dB/cm and 0.3 dB/point, respectively. In addition, as seen in Fig. 3, both spectra had a discontinuity at 550 nm, which almost corresponds to the cutoff wavelength for the E^{22} mode. Similarly, a large loss increase was observed for the curved waveguide spectrum at wavelengths longer than 880 nm, which indicates that the cutoff wavelength for the E^{12} mode is around 880 nm. Thus, the wavelength range of 550–880 nm remains in the quasi-single mode.

A microscope image obtained at the end surface of the eight outputs of the AWG is shown in **Fig. 4**. A range of colors similar to those of the rainbow can be seen at the eight outputs, indicating that the AWG successfully resolved visible light. The transmission spectra of the AWG are shown in Fig. 5(a). The output wavelengths were from 442 to 700 nm with the smallest insertion loss of 5 dB at output 7 (671.4 nm). The 3-dB bandwidths were 15 nm. As described above, the cutoff wavelength of the E^{22} mode was around 550 nm, causing an excess loss of 4 dB at output 3 (531.4 nm). Unfortunately, the optical power of the halogen lamp we used in this experiment was too

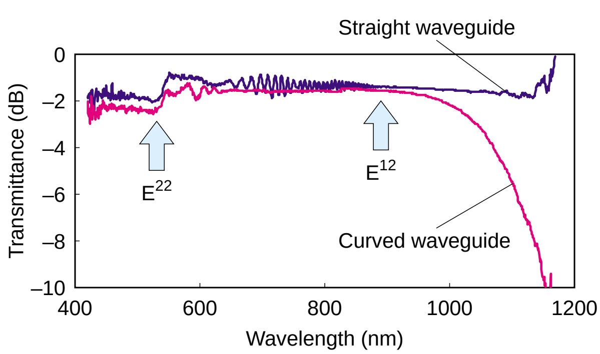


Fig. 3. Transmission spectra of straight and bent waveguides in the wavelength range from visible to near infrared.

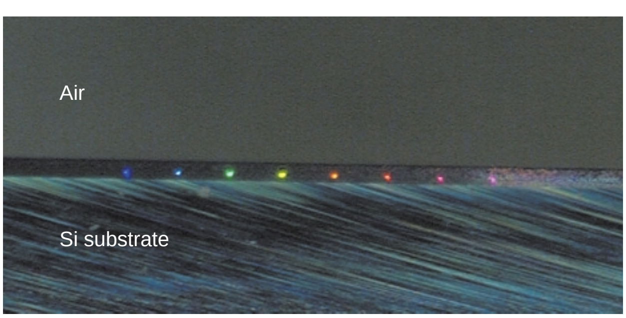


Fig. 4. Microscope image of eight outputs of wide-range AWG.

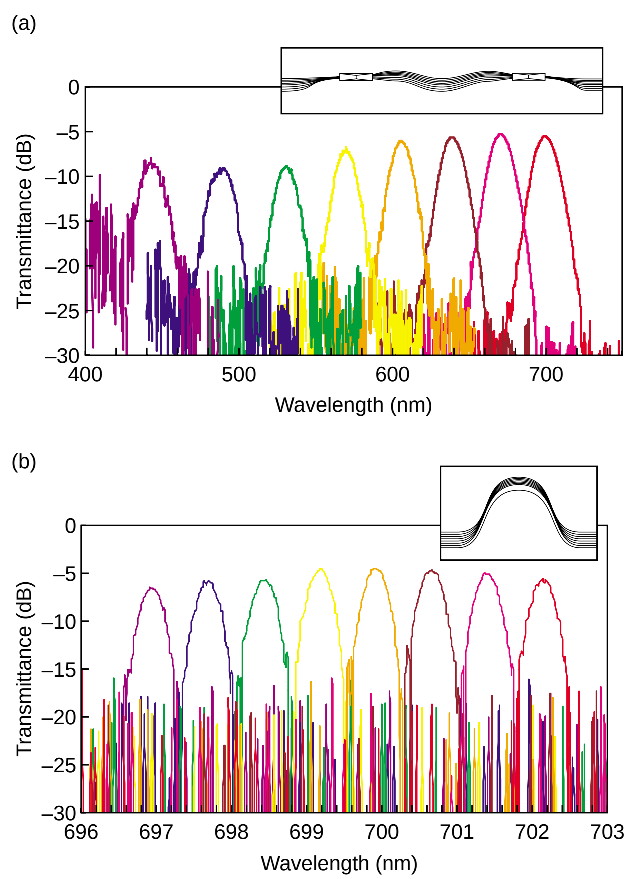


Fig. 5. Transmission spectra of (a) wide-range AWG and (b) narrowband AWG for visible wavelengths.

weak to enable us to observe the true crosstalk. However, we can say that it is less than –25 dB from our observation of the crosstalk around 700 nm.

The transmission spectra of the AWG with narrow output wavelength spacing is shown in Fig. 5(b). The output wavelength ranged from 697.9 to 702.1 nm, and the measured channel spacing was 0.75 nm as expected. The insertion loss and the 3-dB bandwidth were 4.5 dB for the center output (699.1 nm), and 0.34 nm, respectively. The narrowband AWG for visible wavelengths clearly meets the requirements for fine-wavelength-resolution applications.

4. Conclusion

We demonstrated arrayed-waveguide gratings for the visible wavelength range. First, we designed the waveguide parameters by optimizing the dispersion of the waveguides to minimize their bending loss. The measured propagation loss was 0.4 dB at a wavelength of 630 nm, which is sufficiently small for optical circuits. Then, we used these parameters to design and fabricate two types of AWGs: one with outputs ranging from 400 to 700 nm and the other with a narrow output-wavelength spacing of 0.75 nm and a center wavelength of 700 nm. We observed rainbow-like colors at the outputs of the first AWG. The minimum insertion loss was 4.5 dB for the second AWG. Both AWGs have good spectroscopic characteristics, and the results potentially expand the application area of silica-based AWGs. AWGs are now available for wavelengths from visible to near infrared.

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