Cyclic Arrayed Waveguide Grating Devices With Flat-Top Passband and Uniform Spectral Response

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***Abstract*—Cyclic arrayed waveguide grating (AWG) devices with flat-top passband and uniform spectral response are proposed. Each access waveguide of the proposed cyclic AWG consists of a multimode interference region and a taper waveguide. Simulation results show that the 1-dB bandwidth of the proposed device is larger than 0.44 times the channel spacing and the corresponding nonuniformity is smaller than 1 dB.**

***Index Terms*—Arrayed waveguide grating (AWG), cyclic, flat-top, spectral response.**

I. Introduction

OPTICAL networks are widely used in modern communication systems. The use of optical devices with good characteristics such as wide bandwidth, compact size, high fabrication tolerance, stable output, polarization independence, low power loss, etc., is becoming more and more important. Arrayed waveguide gratings (AWGs) are the key devices for wavelength-division multiplexers/demultiplexers and wavelength routers [1] in backbone optical networks. In recent years, fiber-to-the-home has been built gradually, the use of cyclic AWG in any wavelength bands is paid attention to and studied for its expansibility.

However, the passband is not flat-topped and the spectral response is not uniform for conventional cyclic AWG. Those require a light source of high accurate wavelength in order to have several signals with different wavelengths be multiplexed by an AWG and coupled into the same access fiber. In principle, the spectral response of cyclic AWG has a 3-dB nonuniformity [1]. Thus, variable optical attenuators are necessary to equalize the powers between the output signals [2], [3]. It would then be too expensive to use a variable optical attenuator for each channel in an AWG of 200 channels for commercial application.

Therefore, flat-topped passband [4] and uniformed spectral response are of great importance in order to have signals be equally multiplexed/demultiplexed by the same AWG and coupled into an access fiber.

To reduce the transmission loss, multimode interference (MMI) structures with taper access waveguides were reported in splitter and coupler applications [5], [6]. In this paper, the MMI structure with a taper access waveguide is used between the second slab and the output access waveguides of a cyclic AWG to improve the device characteristics. With a proper design of each access waveguide, the calculated spectral response is found uniformed and the passbands are flat-topped.

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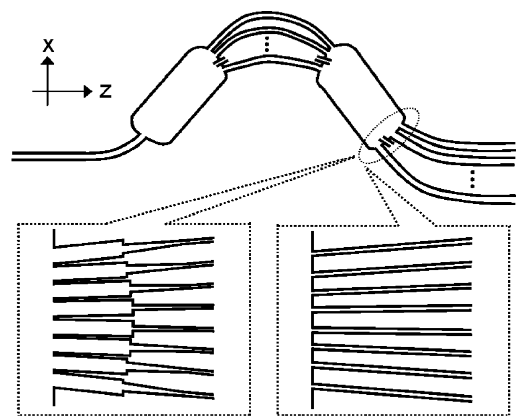

(a) (b)

Fig. 1. Cyclic AWG (a) proposed and (b) conventional.

II. Proposed Cyclic AWG

The proposed cyclic AWG, shown in Fig. 1(a), consists of a cyclic AWG and many MMI structures with taper access waveguides. The MMI structures are used to have the passbands flat-topped, whereas the linear-taper waveguides are introduced to obtain a uniformed spectral response.

A. Cyclic AWG

The cyclic AWG structure consists of an input waveguide, a first slab waveguide, arrayed waveguides, a second slab waveguide, and output access waveguides as shown in Fig. 1(b). The path length difference ΔL between adjacent arrayed waveguides can be written as [1]

$$\Delta L = \frac{c}{\widetilde{N}_g \cdot N \cdot \Delta f} \tag{1}$$

where N is the number of channels, Δf is the channel spacing, and $\widetilde{N}_g$, the group index of waveguide mode, is equal to

$$\widetilde{N}_g = N_g + f \cdot \frac{dN_g}{df} \tag{2}$$

where N_g is the effective index of waveguide mode. The radius of outer Rowland circle R_a is

$$R_a = \frac{d_a}{\Delta\alpha} \tag{3}$$

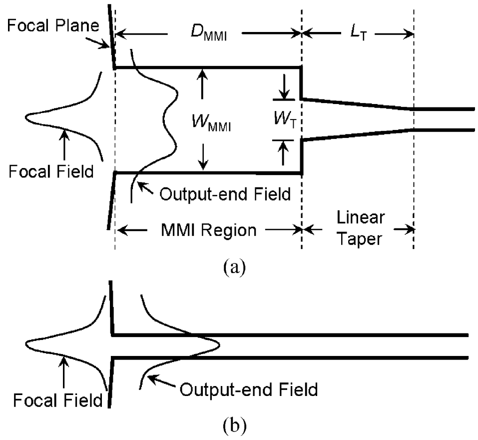

Fig. 2. Output-end structure of cyclic AWG. (a) MMI structure with a taper (proposed) and (b) conventional.

where d_a is the lateral spacing (center-to-center) of arrayed waveguides and $\Delta\alpha$, the divergence angle, is given by

$$\Delta\alpha = \frac{\tilde{N}_g \cdot \Delta L}{f_c \cdot N_{\rm FPR} \cdot D} \tag{4}$$

where f_c is the central frequency, $N_{\rm FPR}$ is the slab mode index in the free propagation region, and D is the dispersion of array and can be written as

$$D \equiv \frac{ds}{df} = \frac{ds}{d\lambda} \cdot \frac{\lambda^2}{c} \tag{5}$$

where ds is the lateral displacement of focal spot (center-to-center).

According to the operational principle of AWG, signals of different wavelengths are focused on the same focal plane of the second slab waveguide. In general, the field distribution of the output access waveguide of the AWG is a Gaussian-like function as shown in Fig. 2(b). Thus, signals focused at the center of the output access waveguide give rise to the largest transmission, and elsewhere, smaller transmission. Therefore, the passband of the spectra is Gaussian-like.

B. MMI Structure With Taper Access Waveguide

In order to compensate both the Gaussian-like distribution of the passband and the nonuniformity of the output spectrum, an MMI coupler with taper access waveguide is proposed. The proposed MMI coupler is essentially a truncated 1×2 MMI power splitter that does not have two distinct peak powers. The coupling length of a 1×2 MMI splitter $L_{\rm MMI}$ can be written as [7]

$$L_{\rm MMI} \cong \frac{n_g}{2\lambda} \cdot W_{{\rm MMI},e}^2 \tag{6}$$

where n_g is the waveguide index, λ is the signal wavelength, and $W_{\rm MMI}$ and $W_{{\rm MMI},e}$ are the physical and the effective width of interference region. The interference length of the MMI region $D_{\rm MMI}$ ($D_{\rm MMI} < L_{\rm MMI}$) can be shortened to obtain two overlapped rather than two distinct peak power distributions as shown in Fig. 2. When the incident Gaussian beam passes through such a truncated 1×2 MMI splitter, the output power distribution of each passband can be significantly flattened due to opposite power distributions. Therefore, the output power distributions of passbands can be flat-topped though the entire spectrum is not uniform, as shown in Fig. 3(a).

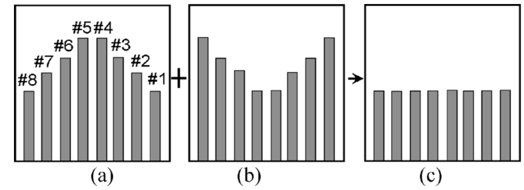

Fig. 3. Illustration of relative transmission of each channel by selecting a suitable value of W_T. (a) With MMI structure only; (b) with taper only; (c) with both MMI structure and a taper (compensated results).

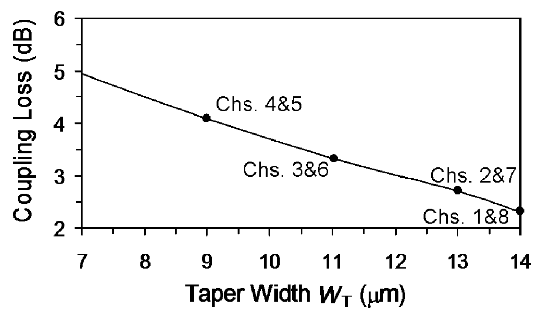

Fig. 4. Calculated coupling loss of each tapered output channel.

To have the spectrum uniformed, the width of each taper access waveguide W_T can be properly chosen for a specific transmission, as shown in Fig. 3(b). Thus, the entire spectrum can be uniformed, as shown in Fig. 3(c).

III. Simulation Results

As silicon photonics are paid much attention [8], the waveguide structure of silicon-on-insulator (SOI) is chosen for study. The indexes of silicon waveguide and silica cover are chosen as 3.4 and 1.45. For practical application, a 1×8 200-GHz-spaced cyclic AWG is proposed and simulated by the finite-difference beam propagation method. Assume the waveguide width is 5 μm and the etch depth and slab thickness are both equal to 3 μm. The central wavelength is set to be 1.55 μm. The corresponding free-spectral range (FSR), defined as $N\Delta\lambda$, is found to be 12.8 nm. The grating order $\lambda/{\rm FSR}$ is equal to 121. The values of ds and d_a are set to be 26 and 18.5 μm, respectively. From (1), ΔL can be calculated to be 55.23 μm. From (3), R_a is found to be 8.44 mm and is chosen as the slab focal length.

The two-peak field distribution of the proposed cyclic AWG with MMI structure and taper access waveguide for flap-top compensation can be chosen with a specific value of $D_{\rm MMI}$. Moreover, the transmission loss of the proposed cyclic AWG with MMI structure and taper access waveguide is shown in Fig. 4. As can be seen, the transmission loss is linearly decreased with an increasing W_T. A proper transmission loss for each channel of AWG can be realized by choosing a suitable W_T. As the transmission loss of each channel can be individually selected to make the spectral response uniform on the same chip,

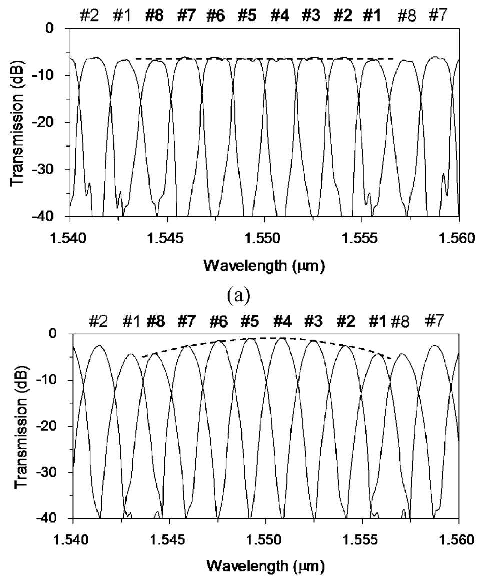

Fig. 5. Spectra of cyclic AWG (a) proposed and (b) conventional.

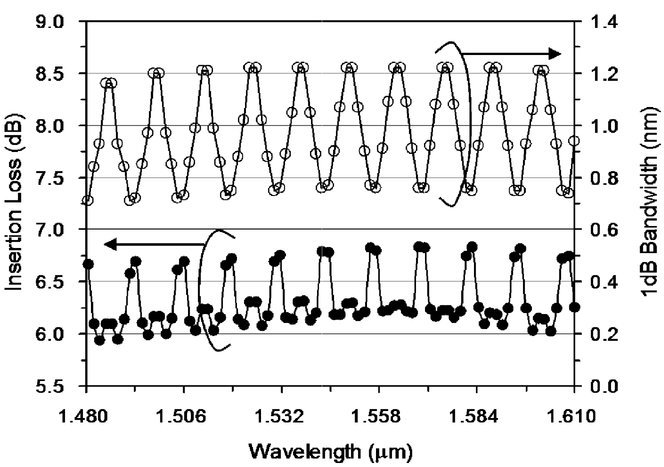

Fig. 6. Variation of insertion loss and 1-dB bandwidth of proposed cyclic AWG for over-all operating wavelength range.

several devices can be integrated to become a module-on-a-chip such as wavelength cross connect and wavelength-division-multiplexing modulator, etc. The proper values of D_{MMI} are equal to 635, 630, 620, and 570 μm and the corresponding values of W_T are equal to 9, 11, 13, and 14 μm, respectively. Note that the values of W_{MMI} and L_T are fixed to be 24 and 500 μm, respectively for simplicity.

The spectra of the proposed 1×8 200-GHz-spaced cyclic AWG are shown in Figs. 5(a) and 6. As can be seen from figures, the 1-dB bandwidth are all larger than 0.44 times the channel spacing and the nonuniformity is smaller than 1 dB for the operational wavelength range is varying from 1.48 to 1.61 μm, which is wide enough for ten cyclic bands. For comparison, the spectra of the conventional cyclic AWG are shown in Fig. 5(b). Obviously, the spectral response of the proposed cyclic AWG is uniformed and all the passbands are nearly flat-topped as compared to those of the conventional cyclic AWG.

Nevertheless, the total transmission loss of the proposed cyclic AWG with MMI structures and taper access waveguides is increased. For example, the increased loss is about 2.3 dB when the taper width is 14 μm, but becomes 4.1 dB when the taper width is 9 μm, as shown in Fig. 4. That is an inevitable trade-off for the compensation of the nonuniformity of cyclic AWG. However, it can be easily overcome by an erbium-doped fiber amplifier.

Obviously, the bandwidths of passbands are not the same. However, the 1-dB bandwidths of the passbands are all larger than 0.44 times the channel spacing, which are better than the performance criterion of GR-1209-CORE (0.35 times the channel spacing) [9].That is more important for practical application.

IV. Conclusion

Cyclic AWG devices with flat-top passband and uniform spectral response can be obtained by using an MMI region and a taper access waveguide for each output access waveguide of the cyclic AWG. Simulation results show that the 1-dB bandwidth can be as wide as 0.44 times the channel spacing and the nonuniformity is smaller than 1 dB. Details of the application will be of great interest for future study.

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