LETTER
IEICE Electronics Express, Vol.12, No.9, 1–6

Design and characterization of an arrayed-waveguide grating router with an interleave-chirped array

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Abstract: The loss uniformity of an arrayed-waveguide grating router was improved by employing an interleave-chirped arrayed-waveguide grating, without increasing the maximum loss. We fabricated a 16×16, 50-GHz channel-spacing, interleave-chirped arrayed-waveguide grating router for use in 1-µm wavelength band communications. The minimum loss, the maximum loss, and the loss uniformity were 5.4 dB, 7.0 dB, 1.6 dB, respectively.
Keywords: planar lightwave circuit, arrayed-waveguide grating, arrayed-waveguide grating router, AWG, AWGR, interleave-chirp
Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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DOI: 10.1587/elex.12.20150261
Received March 16, 2015
Accepted March 19, 2015
Publicized April 9, 2015
Copyedited May 10, 2015

IEICE Electronics Express, Vol.12, No.9, 1–6

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1 Introduction

New optical-waveband communication technologies are essential to increase transmission capacity from the perspective of wavelength division multiplexing (WDM). An all-band photonic transport system for the 1–2 µm wavelength band [1], and a demultiplexer with 600 nm total bandwidth have been proposed [2]. A transmission experiment for the 1-µm band, C-band, and L-band has been reported [3] using a holey fiber as the ultra-broadband transmission line. The 1-µm band is called the 'Thousand-band' (T-band: 1.000–1.260 µm) [4], and the bandwidth of the T-band is 60 THz. In the T-band, the number of WDM signals will reach 1200 when the channel spacing is 50 GHz. A relatively high number of wavelength channels are well suited to use in wavelength routing because the number of channels can be equal to the number of users. An arrayed-waveguide grating router (AWGR) has the potential to realize non-blocking interconnections using this numerous wavelength channels approach [5].

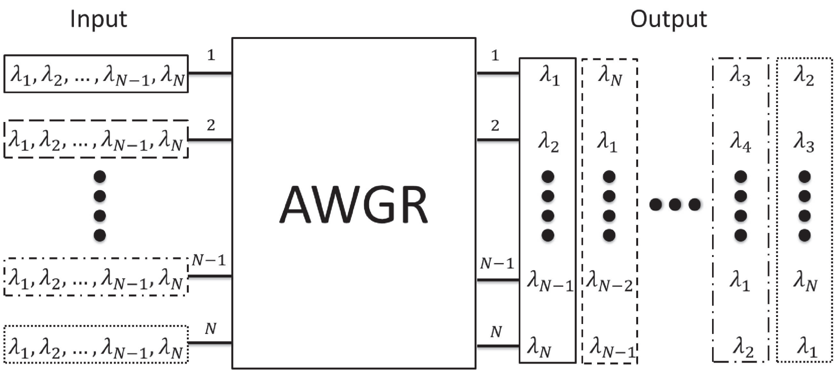

Fig. 1. N × N interconnections of the AWGR.

The AWGR is a planar lightwave circuit that enables N wavelength channels to make N × N strictly non-blocking interconnections, as shown in Fig. 1. The design rule for a conventional N × N AWGR is that the free spectral range (FSR) is equal to the product of N and the channel spacing [6]. The conventional AWGR suffers from two problems, namely very non-uniform losses and peak frequency devia-

DOI: 10.1587/elex.12.20150261
Received March 16, 2015
Accepted March 19, 2015
Publicized April 9, 2015
Copyedited May 10, 2015

tions. The loss uniformity of a conventional AWGR is about 5 dB, which is defined as the difference between the maximum loss and the minimum loss among a combination of input ports and output ports. To improve these characteristics, a uniform-loss and cyclic-frequency (ULCF) configuration and an interconnected multiple AWG configuration have been reported [7]. These configurations exhibit good characteristics; however, the former requires a large number of 3-dB couplers and waveguide crossings, and the latter requires a large number of AWGs.

An improvement in loss uniformity can be realized by attenuation of the optical power of the light from low-loss ports; however, this approach causes considerable excess loss. There are several reports on more efficient methods to improve loss uniformity [8, 9, 10, 11, 12, 13]. We proposed an interleave-chirped arrayed-waveguide grating router (IC-AWGR) to improve loss uniformity [14]. The IC-AWG has been reported as a component of wavelength selective cross connects [15] and a multi-wavelength coherent receiver [16]. The weakness of the IC-AWGR and these devices [8, 9, 10, 11, 12, 13] is peak frequency deviations. However, this problem can be solved by employing a flat-topped passband [17] in the AWG.

In this paper, we have fabricated the 16 × 16, 50-GHz channel-spacing IC-AWGR for T-band communications based on the previously proposed design [14]. The improvement in loss uniformity of the IC-AWGR is demonstrated by calculations and experiments. Conventionally, the loss uniformity characteristics were improved in some degree by the optimization of the structures between an arrayed-waveguide and a slab waveguide [8, 9, 10, 11]. The design that was reported in [12] requires a large number of 3-dB couplers and waveguide crossings. On the other hand, the IC-AWGR requires that the FSR is twice that of a conventional AWGR, and the path difference in the array is not constant.

2 IC-AWGR configuration

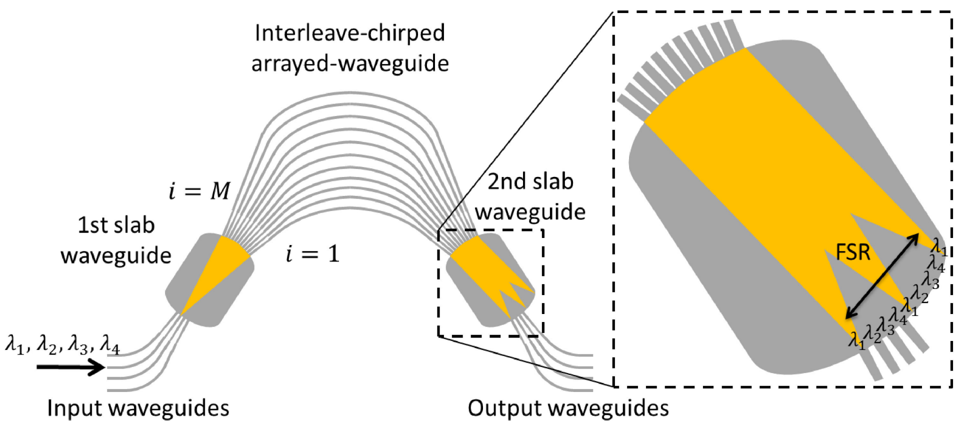

Fig. 2. Schematic of a 4 × 4 IC-AWGR.

Fig. 2 shows a schematic of a 4 × 4 IC-AWGR which consists of input waveguides, two slab waveguides, an interleave-chirped arrayed-waveguide, and output waveguides. The length of the i-th waveguide in the interleave-chirped arrayed-waveguide, L_i, is given by [15].

DOI: 10.1587/elex.12.20150261
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Copyedited May 10, 2015

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$$L_i = L_1 + (i-1)\Delta L, \quad i\text{: odd number.} \tag{1}$$

$$L_i = L_1 + (i-1)\Delta L + \frac{\lambda_0}{4n_c}, \quad i\text{: even number.} \tag{2}$$

The length of the shortest waveguide in the arrayed-waveguide is L_1. ΔL is the path difference, λ_0 is the center wavelength of the AWGR, and n_c is the effective index of the arrayed-waveguide. The input light is spatially dispersed and has two images in the FSR. The lengths of the even-numbered waveguides are chirped by $\lambda_0/4/n_c$, which corresponds to a phase of $\pi/2$ at the center wavelength. The peak transmittance of the IC-AWGR is 3-dB lower than that of a conventional AWGR due to power-splitting at the 2nd slab waveguide. The IC-AWGR operates as though the FSR is halved. Therefore, the IC-AWGR shows $\mathrm{N} \times \mathrm{N}$ cyclic characteristics when the FSR is equal to the product of 2N and the channel spacing. The slab length of the $\mathrm{N} \times \mathrm{N}$ IC-AWGR is twice as long as that of a conventional $\mathrm{N} \times \mathrm{N}$ AWGR. Therefore, the loss uniformity is improved because the Gaussian diffraction pattern from a waveguide in the array becomes twice as wide as that of a conventional AWGR.

3 Design and experimental results

We have designed and fabricated a 16×16 IC-AWGR using silica waveguides. Table I shows the design parameters of a 16×16 IC-AWGR.

Table I. Design parameters of a 16×16 IC-AWGR.

Parameter	Value
Relative refractive index difference	1%
Waveguide core dimension	4 µm × 4 µm
Center wavelength	1150 nm
Channel spacing	50 GHz
FSR	1600 GHz
Diffraction order	160
Path difference, ΔL	126.2 µm
Number of waveguides in array	96
Slab waveguide length	5855.4 µm
Length of chirp	197 nm

Fig. 3 shows the loss calculations of a 16×16 AWGR and a 16×16 IC-AWGR, respectively. The propagation of the light in the slab waveguide was calculated using spatial Fourier transform with an effective index method. The coupling efficiency of the light between a slab waveguide and a waveguide array was obtained by the numerical computation of the overlap integral. All combinations between the input ports and the output ports were calculated. The AWGR and the IC-AWGR both show Gaussian-like loss profiles. The minimum losses of the AWGR and the IC-AWGR were 1.3 dB and 4.3 dB, respectively, when the 9th input port and the 9th output port were connected. The maximum losses of the AWGR and the IC-AWGR were 5.7 dB and 5.4 dB, respectively. The combination of the AWGR that shows the maximum loss was between the 16th input and the 16th

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output port. The combination of the IC-AWGR that shows the maximum loss was between the 16th input and the 1st output port. The loss uniformity of the AWGR and the IC-AWGR were 4.4 dB and 1.1 dB, respectively. The IC-AWGR shows improved loss uniformity and reduction of the maximum loss compared to the AWGR.

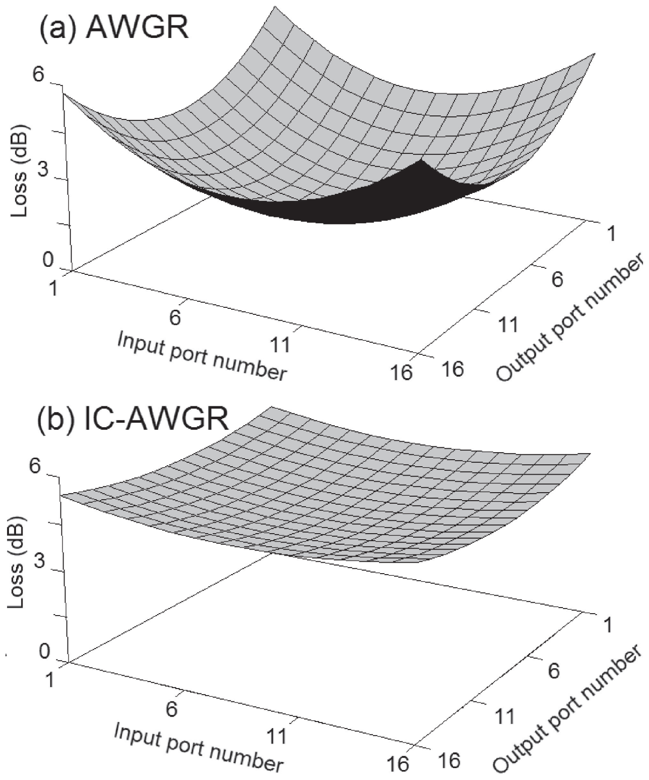

Fig. 3. Loss calculations of (a) AWGR and (b) IC-AWGR.

The transmission spectra of the IC-AWGR were measured using a super-continuum light source and an optical spectrum analyzer. Fig. 4 shows the transmission spectrum between the central input (9th) waveguide and the central output (8th) waveguide. The propagation loss and the coupling losses between the fiber and the waveguide were subtracted. The loss of the IC-AWGR was 6.5 dB, and the crosstalk of the IC-AWGR was −28.7 dB. The increase of crosstalk is due to interleaved-chirp. The 3-dB bandwidth of the IC-AWGR was 0.15 nm.

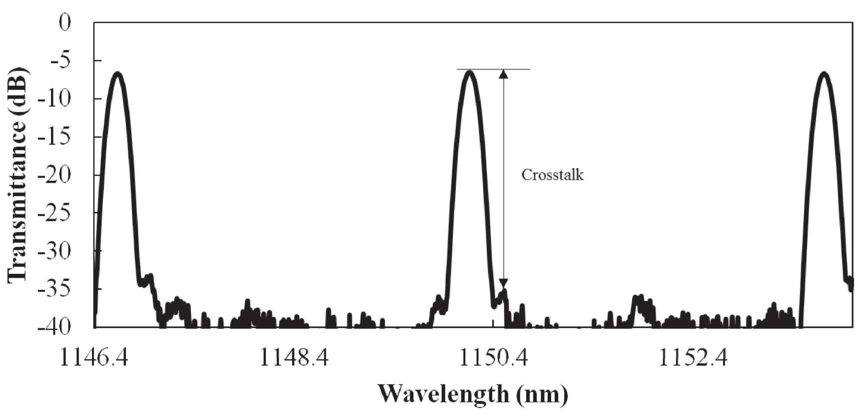

Fig. 4. Transmission spectrum of the 16 × 16 IC-AWGR.

DOI: 10.1587/elex.12.20150261
Received March 16, 2015
Accepted March 19, 2015
Publicized April 9, 2015
Copyedited May 10, 2015

ELectronics EXpress
IEICE Electronics Express, Vol.12, No.9, 1–6

From the simulation results shown in Fig. 3, it is clear that the combination that produces the minimum loss is between the central input and the central output, and that of the maximum loss is between the edge input and the edge output. Table II shows the losses of several combinations of input and output ports. The maximum loss was 7.0 dB between the central input (9th) and the edge output (1st). The minimum loss was 5.4 dB between the edge input (1st) and the central output (8th). The loss uniformity was 1.6 dB which was very close to calculation value of 1.1 dB. The loss between the central input and the central output was not the minimum loss, and that between the edge input and the edge output was not the maximum loss due to alignment errors at waveguide facets.

Table II. Losses between input and output.

In	Out	Loss (dB)
1	1	6.4
1	8	5.4
1	16	6.4
9	1	7.0
9	8	6.5
9	16	6.9
16	1	6.0
16	8	5.5
16	16	6.1

4 Conclusion

We fabricated a 16×16 IC-AWGR and measured its characteristics. The channel spacing and the center wavelength were 50 GHz and 1150 nm, respectively. The loss and the crosstalk of the 16×16 IC-AWGR were 6.5 dB and -28.7 dB, respectively. The loss uniformity was 1.6 dB, which was lower than the value of about 5 dB for a conventional AWGR.

Acknowledgments

The results in this work have been achieved through “Research and development on photonic networks using the broad wavelength range of the T- and O-bands”, a research project commissioned by the National Institute of Information and Communications Technology (NICT), Japan.

DOI: 10.1587/elex.12.20150261
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Copyedited May 10, 2015