Parameter Optimization of a 9 × 9 Polymer Arrayed Waveguide Grating Multiplexer

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(Received 2 November 2001)

Some important parameters are optimized for a 9 × 9 polymer arrayed waveguide grating multiplexer around the central wavelength of 1.55 μm with the wavelength spacing of 1.6 nm. These parameters include the thickness and width of the guide core, diffraction order, pitch of adjacent waveguides, path length difference of adjacent arrayed waveguides, focal length of slab waveguides, free spectral range, the number of input/output channels and the number of arrayed waveguides. Finally, a schematic waveguide layout of this device is presented, which contains 2 slabs, 9 input and 9 output channels, and 91 arrayed waveguides.

PACS: 42. 79. Sz, 42. 82. Gw

The arrayed waveguide grating (AWG) multiplexer is a key device for wavelength division multiplexing in optical telecommunication systems.[1−6] Recently, polymer AWG multiplexers have attracted particular attention because of their excellent particular features, such as easier fabrication, lower propagation loss, better thermal stability and smaller birefringence. Many research groups have fabricated such optical devices using various polymeric materials.[7,8]

In this Letter, we report in detail on the parameter optimization of a 9 × 9 polymer AWG multiplexer around the central wavelength of 1.55 μm with the wavelength spacing of 1.6 nm. Finally, the schematic waveguide layout of this device is presented.

The schematic diagram of the AWG multiplexer studied in this work is shown in Fig. 1. This device consists of $2N$+1 input channels, $2N$+1 output channels, two focusing slabs, and an AWG which contains $2M$+1 arrayed rectangular waveguides, all of which are integrated on the same substrate. The material of the guide core is epoxypropyl methylacrylate-co-methyl methacrylate polymer and bisphenyl-A epoxy mixture whose refractive index is taken to be n_1= 1.495. The material of the cladding surrounding the guide core is epoxypropyl methylacrylate-co-methyl methacrylate polymer whose refractive index is taken to be n_2= 1.483. Then the relative refractive index difference between them is $\Delta n = (n_1\text{-}n_2)/n_1 = 0.8\%$. The above data were measured by Woollam, Lincoln, NE, USA. In the following analysis, the central wavelength is selected to be $\lambda_0 = 1.550918\,\mu$m and the wavelength spacing $\Delta\lambda = 1.6$ nm.

The eigenvalue equations of the $E^y_{\rm mn}$ mode for the rectangular waveguide are as follows

$$k_x a = p\pi + 2\arctan\left(\frac{q_x}{k_x}\right), \quad (p = 0, 1, 2, \cdots), \tag{1}$$

$$k_y b = q\pi + 2\arctan\left(\frac{n_1^2 q_y}{n_2^2 k_y}\right), (q = 0, 1, 2, \cdots), \tag{2}$$

where Eq. (2) is also the eigenvalue equation of the TM_n mode of the slab waveguide, a and b are the width and thickness of the guide core, p and q are the mode order numbers, and λ is the wavelength in free space.

Figure 2 shows the relations between the core thickness b and the effective refractive indices n_s and n_c for the central wavelength. It is found that we must select the core thickness b within the range of $2.4 - 4.2\,\mu$m to realize the single-mode propagation of both the TM_0 mode in the slab and the E^y_{00} mode in the rectangular waveguide.

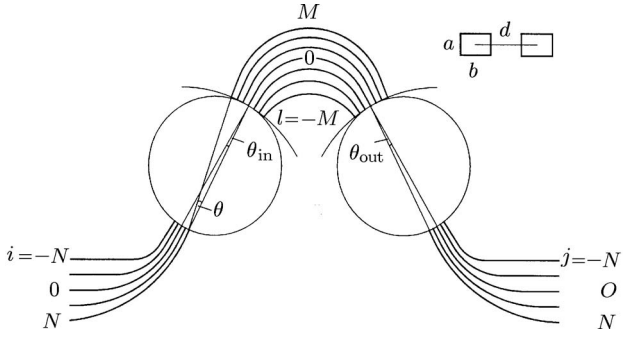

Fig. 1. Schematic diagram of an AWG multiplexer.

The coupling effect exists among the arrayed waveguides. In order to weaken the coupling between

*Supported by the National Natural Science Foundation of China Under Grant Nos 60177022 and 69937010, the National Key Fund of Research Development and the National High Technique Research Development of China Under Grant Nos G2000036604 and 2001AA312160.

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two waveguides of length l, the following equation is used to determine the pitch d of adjacent waveguides[9]

$$d = a + \frac{1}{q_x} \ln \left(\frac{2lk_x^2 q_x}{a|T|k_c \left(k_x^2 + q_x^2\right)} \right), \tag{3}$$

where $|T|$ is the power transfer coefficient.

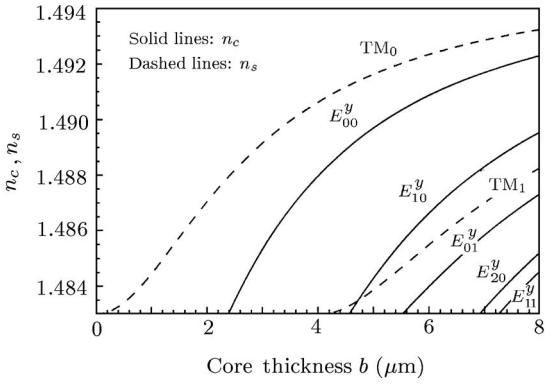

Fig. 2. Relations between the core thickness b and the effective refractive indices n_s and n_c, where $a = 1.5b$ and $\lambda_0 = 1.550918$ μm.

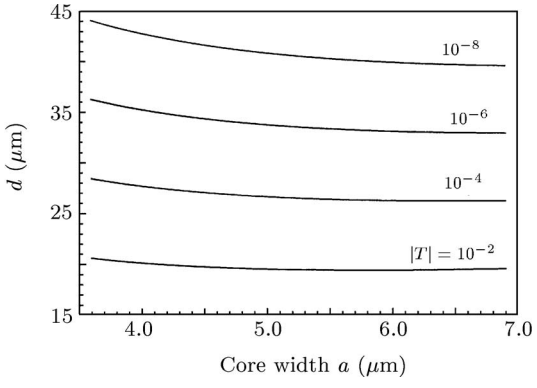

Fig. 3. Relation between the core width a and the guide pitch of adjacent waveguides d, where $a = 1.5b$, $\lambda_0 = 1.550918$ μm, $l = 1$ cm, and $|T| = 10^{-2}$, 10^{-4}, 10^{-6} and 10^{-8}.

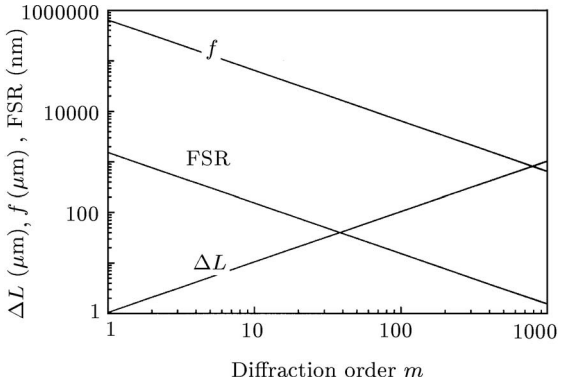

Fig. 4. Relations between the diffraction order m and the path length difference of adjacent arrayed waveguides ΔL, focal length f and free spectral range, where $b = 4$ μm, $a = 6$ μm, $d = 26.5$ μm, and $\lambda_0 = 1.550918$ μm.

Figure 3 shows the relation between the core width a and the pitch d for the central wavelength. It can be seen that, as the core width a increases, the pitch d decreases; the smaller the power transfer coefficient $|T|$, the larger the pitch d becomes. When we choose $b = 4\,\mu$m, $a = 6\,\mu$m, $l = 1$ cm, and $|T| \leqslant 10^{-4}$, the pitch d must be larger than 26.2 μm. In this case, the coupling between the waveguides is so weak that it can be neglected. In the practical design of the device we select the pitch $d = 26.5$ μm.

Therefore, in the following calculations the values of some parameters are taken as: core thickness $b = 4\,\mu$m, core width $a = 6$ μm, pitch of adjacent waveguide $d = 26.5$ μm, central wavelength $\lambda_0 = 1.550918$ μm, effective refractive indices $n_s = 1.4906$, $n_c = 1.4879$, and group refractive index $n_g = 1.4963$.

The diffraction order m is an important parameter. Once the diffraction order is determined, some other parameters of the device are also determined, such as the path length difference of adjacent arrayed waveguides, focal length of the slabs, free spectral range, and the numbers of input/output (I/O) channels and arrayed waveguides. In the following analysis we investigate the relations between the diffraction order and the above parameters, and carry on the parameter optimization.

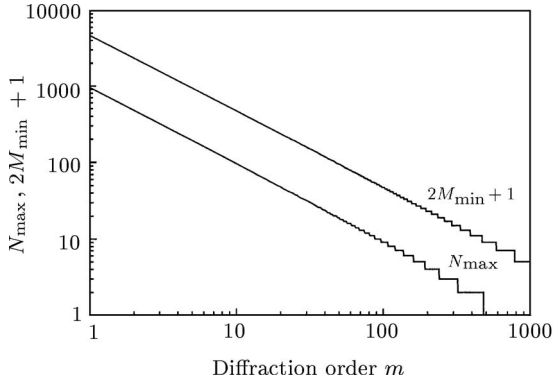

Fig. 5. Relations between the diffraction order m and the maximum number of the input/output channels $N_{\max}$ and the minimum number of the arrayed waveguides $2M_{\min}+1$, where $b = 4$ μm, $a = 6$ μm, $d = 26.5$ μm, and $\lambda_0 = 1.550918$ μm.

The path length difference ΔL, focal length f and free spectral range (FSR) are given by[10,11]

$$\Delta L = \frac{m\lambda_0}{n_c}, \tag{4}$$

$$f = \frac{n_s d^2}{m\Delta\lambda} \frac{n_c}{n_g}, \tag{5}$$

$$d_{\mathrm{FSR}} = \frac{\lambda_0}{m} \frac{n_c}{n_g}, \tag{6}$$

Figure 4 shows the relations between the diffraction order m and the path length difference ΔL, focal

length f and FSR. It can be seen that as the diffraction order m increases, the path length difference ΔL increases, while the focal length f and FSR decrease. Usually the focal length f is taken in the range of 3000–10000 μm, therefore, the diffraction order should be selected in the range of 200–65.

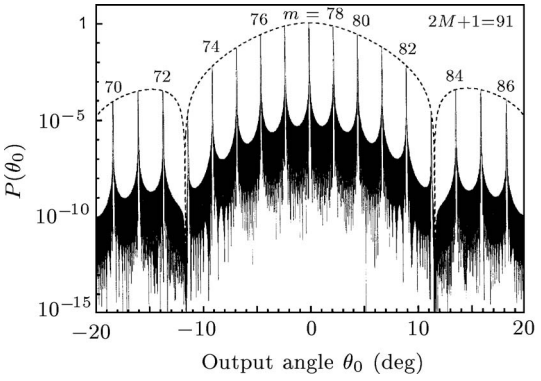

Fig. 6. Power profiles $P(\theta_0)$ in the output slab, where $b = 4\,\mu$m, $a = 6\ \mu$m, $d = 26.5\ \mu$m, $\lambda_0 = 1.550918\ \mu$m, and $2M{+}1 = 91$.

The maximum number of I/O channels $N_{\max}$ depends on the FSR. The bandwidth of the multiplexed light, that is $N_{\max}\Delta\lambda$, must be narrower than the FSR to prevent the overlapping of orders in the spectral region. Accordingly, $N_{\max}$ is restricted as

$$N_{\max} < \frac{d_{\mathrm{FSR}}}{\Delta\lambda} = \frac{\lambda_0}{m\Delta\lambda}\frac{n_c}{n_g}. \tag{7}$$

Therefore, the number of the I/O channels is $2N{+}1 \leqslant N_{\mathrm{man}}$ in a real AWG multiplexer.

The normalized distant field of the central channel in the slab can be written as[12]

$$\begin{aligned} E_0(\theta) = {} & k_x^2 q_x \cos(\theta)\left\{q_x \cos\left[\frac{1}{2}k_s a \sin(\theta)\right]\right. \\ & \left. - k_s \sin(\theta)\sin\left[\frac{1}{2}k_s a \sin(\theta)\right]\right\} \\ & \cdot \left\{\left[k_x^2 - k_s^2 \sin^2(\theta)\right]\left[q_x^2 + k_s^2 \sin^2(\theta)\right]\right\}^{-1}, \end{aligned} \tag{8}$$

where θ is the diffraction angle. The minimum number of arrayed waveguides $2M_{\min}{+}1$ is defined. When the power profile of the central waveguide $P_0(\theta) = E_0^2(\theta)$ is dropped down to $1/e^2$, the relative angle is $\theta = \theta_{\max}$, then we can obtain $M_{\min} = \mathrm{int}(\theta_{\max}/\Delta\theta)$, where $\Delta\theta$ is the angular spacing of adjacent arrayed waveguides given by

$$\Delta\theta = 2\arcsin\left(\frac{d}{2f}\right). \tag{9}$$

Figure 5 shows the relations between the diffraction order m and the maximum number of I/O channels $N_{\max}$ and the minimum number of arrayed waveguides $2M_{\min}{+}1$. It is found that, as the diffraction order m increases, both $N_{\max}$ and $2M_{\min}{+}1$ decrease. In the design of the device presented here, the number of I/O channels is determined to be $2N{+}1 = 9$, so the maximum number of I/O channels can be selected to be $N_{\max} = 10$. Therefore, the diffraction order should be taken as $m = 78$. In this case, the relative values of parameters are as follows: the path length difference of adjacent arrayed waveguides $\Delta L = 81.302\,\mu$m, focal length of the slabs $f = 8340.430\,\mu$m, the FSR is 14.432 nm, and the number of the arrayed waveguides reads $2M_{\min}{+}1 = 91$.

In fact, the number of arrayed waveguides should be taken to be as large as possible. Applying both the waveguide far field and the grating diffraction theory to the AWG, the expression of the normalized power profile $P(\theta_0)$ of all the arrayed waveguides diffracted in the output slab can be derived as

$$\begin{aligned} P(\theta_o) = {} & \left\{E_0(\theta_o)\left[1 + 2\sum_{k=1}^{M} E_0(k\Delta\theta)\cos\left[k\frac{2\pi}{\lambda}\right.\right.\right. \\ & \left.\left.\left. \cdot \left[n_s d\sin(\theta_i) + n_c\Delta L + n_s d\sin(\theta_o)\right]\right]\right] \\ & \cdot \left[1 + 2\sum_{k=1}^{M} E_0(k\Delta\theta)\right]^{-1}\right\}^2, \end{aligned} \tag{10}$$

where θ_i and θ_0 are the input and output angles, respectively, $2M{+}1$ is the number of arrayed waveguides, and $E_0(\theta_0)$ is the envelope function, i.e. the distant field of the central waveguide expressed by Eq. (9). Figure 6 gives the power profiles $P(\theta_0)$ in the output slab for $2M{+}1 = 91$. The larger the number of arrayed waveguides, the narrower and brighter the diffraction pattern, the weaker the background light, and hence the higher the diffraction efficiency. Considering the technical level in our laboratory, we select the number of the arrayed waveguides to be $2M{+}1 = 91$ as well as selecting the number of I/O channels to be $2N{+}1 = 9$ in the practical design of the device.

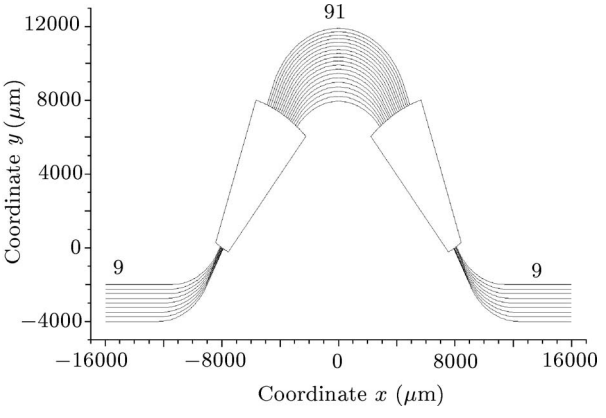

Fig. 7. Schematic waveguide layout of the AWG multiplexer studied in this work, which consists of 2 slabs, 9 input and 9 output channels, and 91 arrayed waveguides.

In short, the above parameters optimized for the design of the AWG multiplexer are listed in Table 1.

Table 1. Parameters used in the design of the AWG multiplexer.

Central wavelength	λ_0	1.550918 μm
Wavelength spacing	$\Delta\lambda$	1.6 nm
Thickness of guide core	b	4 μm
Width of guide core	a	6 μm
Refractive index of guide core	n_1	1.4950
Refractive index of cladding	n_2	1.4830
Effective refractive index of slab waveguide	n_s	1.4906
Effective refractive index of arrayed waveguides	n_c	1.4879
Group refractive index of arrayed waveguide	n_g	1.4963
Diffraction order	m	78
Pitch of I/O and arrayed waveguides	d	26.5 μm
Path length difference of arrayed waveguides	ΔL	81.302 μm
Focal length of slab waveguide	f	8340.430 μm
Free spectral range	d_{FSR}	14.432 nm
Number of I/O channels	$2N+1$	9
Number of arrayed waveguides	$2M+1$	91

Figure 7 presents the schematic waveguide layout of the AWG multiplexer studied in this work. This device consists of 9 input channels, 9 output channels, 91 arrayed waveguides and 2 slabs.

In summary, the method and formulae have been presented for the parameter optimization of a polymer AWG multiplexer, and the relative results and schematic waveguide layout are given. By using this schematic waveguide layout, currently this kind of polymer AWG multiplexer is being fabricated in our laboratory. The values of the parameters in Table 1 calculated by this technique are in good agreement with those calculated by some other techniques.[10,13]

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