Multimode arrayed waveguide grating-based demultiplexers for short-distance communication

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Abstract: A multimode fiber-matched arrayed waveguide grating demultiplexer is presented based on multimode waveguides in the array section. The device, which can be used in short-distance communication, has been realized using low-cost polymer planar waveguide technology.

Keywords: AWG, multimode waveguide, polymeric waveguides, SU-8.

I. Introduction

Multimode fiber and multimode planar waveguide technologies provide robust and very cost-effective solutions in broadband local area networks (LAN's). This major advantage, however, is hindered by the drawback that the bandwidth of the multimode fiber is limited by modal dispersion in contrast to that of the single mode fiber. Of the many schemes proposed to increase the transmission capacity of the multimode fiber-based LAN's, wavelength division (de-)multiplexer (WDM) is the most promising [1].

Multimode fiber-matched WDM represents a serious challenge because of the competition between modal and spectral dispersion. The fabrication of these devices also poses a formidable difficulty, especially due to the need of very low-cost production technologies. A number of multimode fiber-matched WDM has been developed using conventional diffraction gratings [2] or dielectric filters in different design configurations [1].

In this paper we present a novel design of multimode fiber-matched array waveguide grating (AWG) demultiplexer. The design, which utilizes, for the first time, multimode waveguides as array channels has many advantages over other demultiplexers as it can be easily fabricated in a single mask process using low-cost polymer waveguide technology.

After explaining the device principle the design will be given. The fabrication and characterization results will be presented and discussed in section IV. In the last section conclusions will be given.

II. Principle of operation

In Fig. 1a a schematic layout of an array waveguide grating demultiplexer is given. It consists of input and output waveguides connected to a dispersive array of waveguides through two slab couplers. The array is designed in such away that there is a constant length difference between successive waveguides given by

$$\Delta L = \frac{m\lambda_c}{N_{eff,c}} \tag{1}$$

where m is the order of the grating, λ_c is the central wavelength of the demultiplexer, and $N_{eff,c}$ the effective refractive index of the mode in the array channels at λ_c. For the time being we assume that the array channels are single mode. Light propagating at λ_c through the array will arrive with a common phase front at the end of the array and consequently focus on the image plane. When the wavelength is shifted to $\lambda_c+\Delta\lambda$ there will be a linear increase in the phase across the array and the wavefront will be tilted. From Fig. 1b the tilt angle can be inferred to be (see also Refs. [3,4])

$$\theta = \left(\frac{\lambda_c + \Delta\lambda}{N_{eff}} - \frac{\lambda_c}{N_{eff,c}} \right) \frac{m}{d_a} \qquad (2)$$

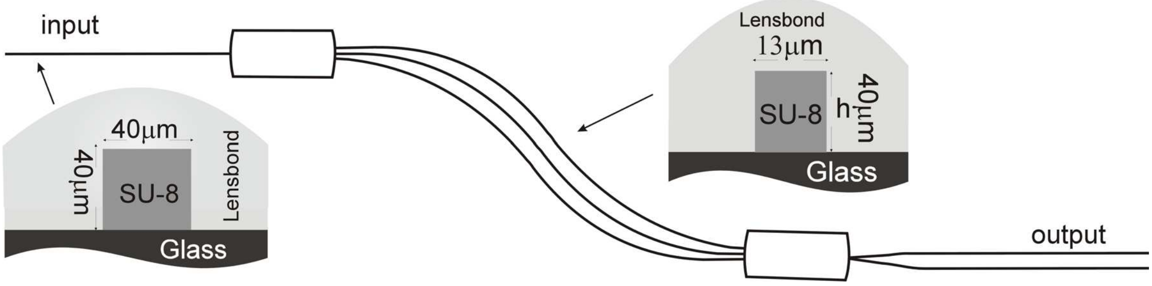
where d_a is the pitch of the array at its aperture. By placing waveguides at the image plane different wavelengths can be selected.

When the array channels are multimode there will be various modes propagating with different speeds in these waveguides. Each of these modes will construct a common wavefront at the end of the array, which is tilted with respect to that of fundamental mode and thus focuses on a different position in the image plane. The maximum tilt angle between the wavefront of the fundamental modes and that of the highest order modes in the array can be obtained from Eq. (2) to be:

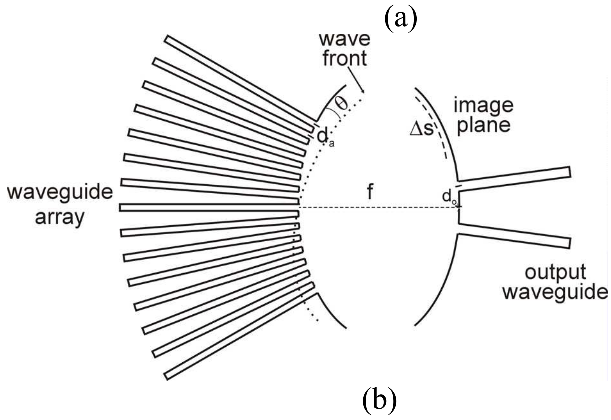
$$\Delta\theta_{md} = \left(\frac{\lambda_c}{N_{eff,j\max}} - \frac{\lambda_c}{N_{eff,0}} \right) \frac{m}{d_a} \qquad (3)$$

where $N_{eff,0}$ and $N_{eff,jmax}$ are the effective refractive indices of the fundamental and highest order mode, respectively. For a realistic design of multimode demultiplexer $\Delta\theta_{md} << \theta$. This can be obtained by using low dispersion gratings, i.e. small m-values, and large spectral channel separation $\Delta\lambda$.

III. Design



(a)



(b)

Fig. 1: (a) Layout of a broadband 1 x 2 AWG with the chosen layer structure. The inserts show the cross section of the waveguide structures.(b) schematic illustration of the output star.

We have designed a 1 x 2 multimode fiber-matched broadband AWG-demultiplexer using highly multimode rectangular waveguides as array channels. In Fig. 1a the basic layout and the waveguide structures of the 1 x 2 demultiplexer are given. The input and the output waveguides are multimode with cross sections of 40 x 40 μm^2 and NA = 0.2. This cross section dimensions and numerical aperture facilitate good coupling to standard multimode fiber with Ø = 50 µm. The array design is based on the anti-symmetrical arrangement [3] for it can be used for demultiplexers with very low dispersion. For the array channels we have used multimode waveguides with cross sections of 13 x 40 μm^2.

In our design we have chosen a channel separation of 100 nm at λ_c = 790 nm. The distance between the two output waveguides is 55 µm and the slab focal length 6.52 mm. The array consists of 16 channels and is operating at a grating order of m = 3. The pitch of the array at the aperture is set to 19 µm.

IV. Fabrication and characterization

The device was fabricated in polymer waveguide technology using the photo-delineation method. The waveguide structure consists of SU-8 photo-resist having a refractive index of 1.58 at λ = 800 nm as a core layer deposited on 1 mm-thick borosilicate substrate with refractive index of 1.47 at λ = 800 nm. For the upper cladding an epoxy called Lensbond mixed with 9-vinylcarbazole (98%) was used. The refractive index of the epoxy is 1.565. Details of the fabrication process can be found in [4,5].

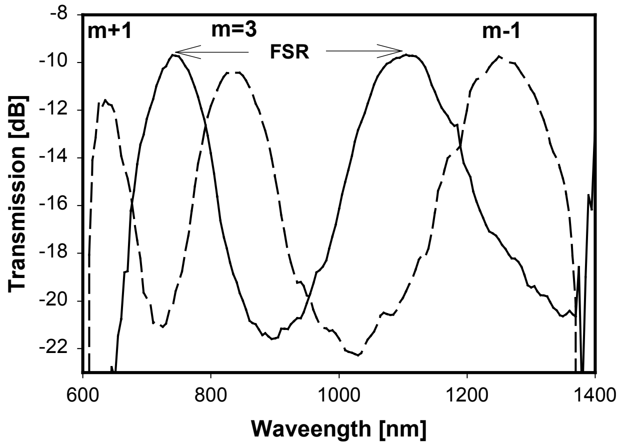


Fig. 2: Transmission spectrum of 1 x 2 AWG-demultiplexer with highly multimode array channels. The transmission is determined with respect to a straight multimode channel waveguide with the same length as the AWG. The two lines (solid and dashed) are the responses obtained at the two output ports.

Optical characterizations of the devices were done using the end-fire coupling method. In the setup a 50/125 µm graded-index multimode fiber was used to couple light in and out of the device. The spectral response of the device was measured using a halogen lamp as a light source and a spectrometer.

Fig. 2 shows the spectral response of the 1 x 2 demultiplexer operating at a central wavelength λ_c = 790 nm. The measured channel spacing, $\Delta\lambda$ = 100 nm and the free spectral range, $\Delta\lambda_{FSR}$ = 395 and 197.5 nm at the longer and shorter wavelength side, respectively, are in good agreement with the designed values. In the figure the response due to orders next to the deign order (m = 3) are also shown. The obtained excess losses are ~ 9.5 dB and the channel cross-talk is about – 9 dB. The largest contribution to the excess loss is probably originated at the slab to array interface. In the ideal case the slab-to-array losses is calculated to be ~ 2.85 dB for a designed gap width of 6 μm between the array channels. The extra measured excess losses are due to irregularities in the gap widths and to the fact that the designed array aperture is smaller than what is required for capturing all the light from the input waveguide. The designed array aperture, $\theta_a = 0.085$ radians, is much smaller than what is predicted using the numerical aperture of the multimode input waveguide, being 0.25 radians. We have also observed that there is significant amount of power lost to the neighboring orders. As can be seen from Fig. 3, the power coupled into the adjacent orders is obviously much higher than what is expected from the design, being only 0.002 dB. This unexpected coupling to undesired orders of the grating might also be due to coupling between the array waveguides caused by irregularity in the widths of the gaps between the channels. The cross-talk is mainly influenced by modal dispersion, the width of the output waveguide, and/or fabrication irregularities. The measured line width is much broader than what is expected from modal dispersion. This increased broadening of the line width could be caused by irregularity in the opening of the gaps between the waveguides at the array apertures and especially by spectral broadening induced by the large width of the in- and output waveguides.

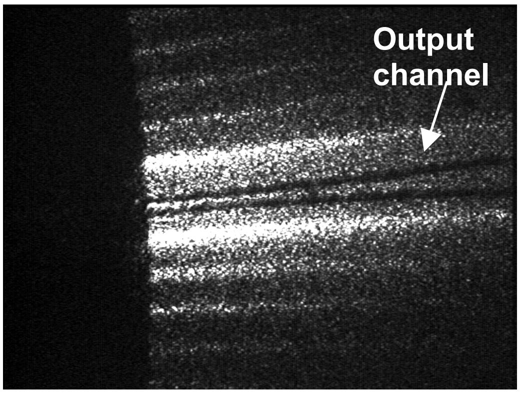


Fig. 3: Optical microscope picture of the curved image plane as schematically given in the right part of Fig. 1 (b) showing the different grating orders of an AWG-demultiplexer with multimode array channels. The two dark lines are the output waveguides.

The polarization dependence of the demultiplexer was measured by launching TE and TM polarized light into the device. The results show that there is no spectral dependence on the polarization and the polarization dependence loss of the device is negligible within the experimental error.

V. Conclusions

Multimode fiber-matched AWG-demultiplexer, employing multimode waveguides as array channels, has been demonstrated. The device was fabricated in low cost polymer waveguide technology. The measured excess loss is 9.5 dB and the cross talk is – 9 dB. The device performance can substantially be improved by further optimizing the design and the fabrication process.

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