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# Design and Realization of Polarization Independent Phased Array Wavelength Demultiplexers using Different Array Orders for TE and TM

L. H. Spiekman, M. R. Amersfoort, A. H. de Vreede, F. P. G. M. van Ham, A. Kuntze, J. W. Pedersen, P. Demeester, and M. K. Smit

**Abstract**—A method for designing polarization independent phased-array wavelength demultiplexers, using different array orders for TE and TM, is described and analyzed with respect to fabrication variations. Flattening of the wavelength response is shown to improve fabrication tolerances. A four channel phased-array wavelength demultiplexer with at least 0.2 nm of polarization independent flattened response for each channel (spacing 1 nm) has been made with an insertion loss of 1.5–3 dB and a crosstalk of –17 to –19 dB.

## I. INTRODUCTION

WAVELENGTH division multiplexing (WDM) is a simple and effective way of exploiting the large bandwidth of optical fibers. The *phased array wavelength (de)multiplexer* [1] has been shown to be the superior WDM (de)multiplexer for systems with a small number of channels [2].

Because of the undefined polarization state of the signal from an optical fiber, this demultiplexer must be polarization-independent. For grating demultiplexers, this can, e.g., be accomplished by exploiting the low polarization dependence of a low contrast slab waveguide [3]. For phased arrays, it has been achieved in a number of different ways, e.g. by insertion of a half wave plate in the middle of the array waveguides [4], by use of nonbirefringent waveguides composed of low bandgap InGaAsP [5], or by a design in which the Free Spectral Range (FSR) equals the waveguide TE–TM shift, thus overlapping different orders of the TE and TM response [6]. The latter approach, which is adopted in our present work, is appealing because it requires no new technology. The most important restriction is that all demultiplexer channels must “fit” within a range equal to the TE–TM shift, which limits the number of channels and/or the channel spacing.

Several designs using this approach have been reported [6]–[8]. In this article, we give a more detailed description of the design of phased array wavelength demultiplexers according to this approach. We will also carry out a tolerance

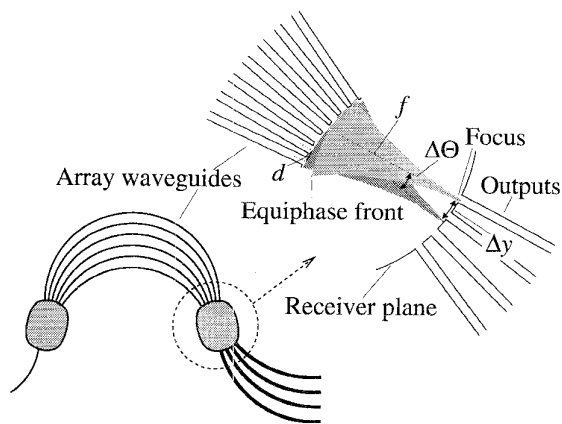


Fig. 1. Operating principle of a phased array: The input field is reproduced in the receiver plane. Tuning the wavelength tilts the phase front, and thus addresses different outputs.

analysis, which shows how the TE–TM shift depends on the waveguide geometry, imposing requirements on process control in order to make TE and TM response overlap. We demonstrate experimentally how these requirements can be relaxed by flattening the demultiplexer response.

## II. OPERATING PRINCIPLE

A phased array demultiplexer consists of a dispersive waveguide array connected to input and output waveguides through two radiative couplers as shown in Fig. 1. Its operation is based on the imaging of the input field onto the output waveguides. Light from an input waveguide diverging in the first star coupler is collected by the array waveguides, which are designed in such a way that the optical path length difference between adjacent waveguides equals an integer multiple of the central design wavelength of the demultiplexer,

$$\Delta l_{\text{optical}} = N_{\text{eff}} \Delta l = m' \lambda_c \quad (1)$$

where  $\lambda_c$  is *in vacuo*. This results in the phase and intensity distribution of the collected light being reproduced at the start of the second star coupler, causing the light to converge and focus on the receiver plane (see Fig. 1). Due to the path length difference, the reproduced phase front will tilt with varying wavelength, thus sweeping the focal spot across different output waveguides.

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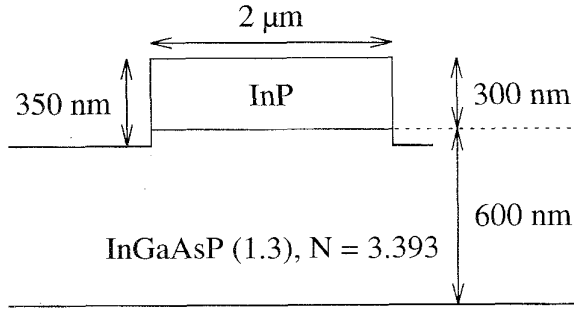
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InP,  $N = 3.171$

Fig. 2. Waveguide structure used in the present design. The refractive indices of the materials are at  $\lambda_c = 1536$  nm, as calculated with the model from [9].

However, in (1),  $m'$  is *not* the order of the demultiplexer,  $m$ , because for this the waveguide and material dispersion must be taken into account. Instead of the phase effective index  $N_{\text{eff}}$ , the group effective index

$$N_g = N_{\text{eff}} - \lambda_c \frac{dN_{\text{eff}}}{d\lambda} \quad (2)$$

must be used, so that we get

$$N_g \Delta l = m \lambda_c. \quad (3)$$

A change  $\Delta\lambda$  in wavelength will advance the phase front at array waveguide  $n$  by  $\Delta\lambda m / N_{\text{eff}}$  more than the phase front at array waveguide  $n - 1$  which lies at a distance  $d$  next to it (see Fig. 1), giving rise to a phase front tilt

$$\Delta\theta \approx \Delta\lambda \cdot \frac{m}{N_{\text{eff}} d} \frac{N_{\text{eff}}}{N_{\text{slab}}} \quad (4)$$

where the rightmost factor is caused by the transition from the waveguides to the free propagation section of the radiative coupler, where the effective index is  $N_{\text{slab}}$ . This tilt leads to a focal spot displacement

$$\Delta y = f \Delta\theta \quad (5)$$

with  $f$  the focal length. Smit [7] describes a procedure to come to a correct array configuration for a desired  $\Delta y / \Delta\lambda$  ratio (i.e., a desired channel spacing given an output waveguide configuration) using only one circularly curved and two straight sections for each array waveguide.

### III. TE-TM SHIFT

Unless special precautions are taken, most planar waveguides are birefringent. Because of the slight difference in the effective indices for TE and TM, wavelengths which are identical *in the waveguide*

$$\frac{\lambda_{\text{TE}}}{N_{\text{TE},\lambda_{\text{TE}}}} = \frac{\lambda_{\text{TM}}}{N_{\text{TM},\lambda_{\text{TM}}}} \quad (6)$$

correspond to unidentical wavelengths *in vacuo*  $\lambda_{\text{TE}}$  and  $\lambda_{\text{TM}}$ . This gives rise to a shift in the wavelength response of a phased array  $\Delta\lambda_{\text{TE-TM}} = \lambda_{\text{TE}} - \lambda_{\text{TM}}$  which, after correcting for the waveguide and material dispersion

$$N_{\text{TM},\lambda_{\text{TM}}} = N_{\text{TM},\lambda_{\text{TE}}} - \Delta\lambda_{\text{TE-TM}} \left( \frac{dN_{\text{TM}}}{d\lambda} \right)_{\lambda_{\text{TE}}} \quad (7)$$

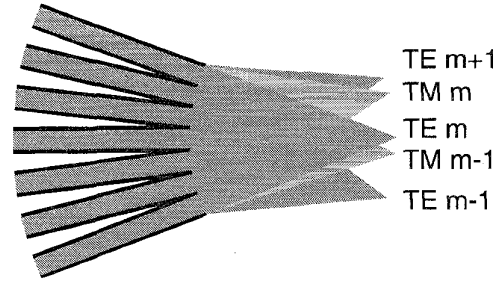


Fig. 3. The different orders radiating from the waveguide array. The waveguide birefringence causes the TE and TM foci to be separated. By properly choosing the Free Spectral Range, the  $\text{TE}_m$  and the  $\text{TM}_{m-1}$  orders can be overlapped.

can be shown to be

$$\Delta\lambda_{\text{TE-TM}} = \lambda_{\text{TE}} \left( 1 - \frac{N_{\text{TM},\lambda_{\text{TE}}}}{N_{\text{TE},\lambda_{\text{TE}}}} \right) \left( 1 - \frac{\lambda_{\text{TE}}}{N_{\text{TE},\lambda_{\text{TE}}} \left( \frac{dN_{\text{TM}}}{d\lambda} \right)_{\lambda_{\text{TE}}}} \right). \quad (8)$$

### IV. POLARIZATION INDEPENDENT DESIGN

In the waveguide structure in which the design described below was fabricated (Fig. 2),  $\Delta\lambda_{\text{TE-TM}}$  is approximately 4.7 nm. A polarization independent four channel demultiplexer with channel spacing 1 nm can be designed in this structure by choosing the array order such that the demultiplexer periodicity, also known as the Free Spectral Range (FSR), equals the TE-TM shift, in order to overlap the  $\text{TE}_m$  and the  $\text{TM}_{m-1}$  demultiplexer orders (shown in Fig. 3):

$$\text{FSR} \approx \frac{\lambda_c}{m} = \Delta\lambda_{\text{TE-TM}}. \quad (9)$$

Although the FSR is not exactly equal to  $\lambda_c/m$ ,<sup>1</sup> the equals sign in (9) is exact. This can be seen by requiring that

$$m' \frac{\lambda_c}{N_{\text{TE},\lambda_c}} = (m' - 1) \frac{\lambda_c}{N_{\text{TM},\lambda_c}} \quad (10)$$

which can be simplified to

$$1 - \frac{N_{\text{TE}}}{N_{\text{TM}}} = \frac{1}{m'}. \quad (11)$$

(Here,  $m'$  is not the demultiplexer order, but the path length difference between adjacent array waveguides from (1), in units of the wavelength in the material!) When the left-hand side of (11) is substituted using (8), and both sides are multiplied by  $m'/m = N_{\text{eff}}/N_g$ , the right-hand equality in (9) follows. Polarization independence is thus obtained by choosing the order

$$m = \frac{\lambda_c}{\Delta\lambda_{\text{TE-TM}}}. \quad (12)$$

### V. FABRICATION TOLERANCE ANALYSIS

Fig. 4 shows the dependence of the TE-TM shift on different waveguide parameters. The data have been calculated with (8), using the model from [9] for taking account of

<sup>1</sup>It is  $\text{FSR}_+ = \lambda_c / (m - (1 - (\lambda_c / N_{\text{eff}}) (dN_{\text{eff}} / d\lambda)))$  and  $\text{FSR}_- = \lambda_c / (m + (1 - (\lambda_c / N_{\text{eff}}) (dN_{\text{eff}} / d\lambda)))$  for the longer and the shorter wavelength side, respectively. The FSR is not a constant here due to the fact that we are working with wavelengths instead of frequencies.

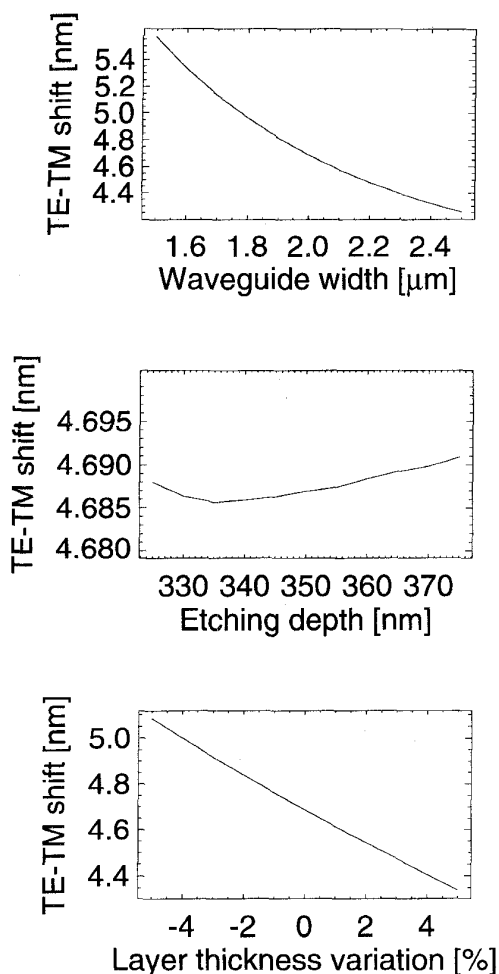


Fig. 4. Dependence of TE-TM shift on several waveguide parameters. The unperturbed waveguide structure is as indicated in Fig. 2. The TE-TM shift hardly depends on the etching depth, but strongly varies with waveguide width and layer thicknesses.

material dispersion, and a scalar Finite Element mode solver for obtaining the effective mode indices. It is seen that  $\Delta\lambda_{\text{TE-TM}}$ , although very tolerant of etch depth variations, is sensitive to layer thickness and waveguide width variations. A layer thickness variation of 3% will cause the TE-TM shift to deviate 0.2 nm from its computed value, as will a waveguide width variation of  $\pm 0.2 \mu\text{m}$ . Thus, practical fabrication tolerances will most likely result in a mismatch of the TE-TM shift and the FSR.

In a “traditional” phased array the response is determined by the overlap integral of the focal spot (which is an image of the input waveguide field) with the modal distribution in the monomode output waveguides, and has a parabolic shape. Therefore, the mismatch has a strong impact on its polarization independence. However, by flattening the wavelength response of the device over a region of at least 0.2 nm, there is, within these practical fabrication tolerances, always a certain wavelength range for each channel in which the device works irrespective of the polarization state of the incoming light. This flattening can be done in the following two ways.

- 1) The focal spot can be modified so that it approximates a rectangular field profile, as proposed in [10], by adding small path length corrections to the phased array arms, changing the phase distribution at the entrance of the output radiative coupler in such a way that its Fourier transform has the desired shape.
- 2) Multimode output waveguides can be used [11], so that the focal spot, exciting different combinations of modes while sweeping across them, always couples efficiently to them within a certain wavelength range.

The former approach has the obvious advantage that it remains possible to couple the output waveguides of the device to monomode fibers, but it always “spills over” a certain amount of light in the flat wavelength region, and thus necessarily exhibits some additional loss with respect to a “traditional” phased array. The latter approach is particularly suitable for application at the receiver end of a system, i.e., by directly integrating photodetectors on the multimode output waveguides. It doesn’t suffer from extra loss, because the output waveguides will collect almost 100% of the light in the focal spot, as long as it is not too close to one of the edges [2]. It should be noted that coupling to a single mode fiber will not be possible when this approach is used, because the loss would depend heavily on the modal pattern in the output waveguides.

## VI. DESIGN EXAMPLE

For proper focusing in the receiver plane, the phase transfer through the array arms must be correct, which means that the device must be as small as possible in order for local variations in waveguide width and layer thickness to have as little influence as possible. But the high order in which the device must operate to fulfill (9) will lead to a large device, and employing (wide) multimode outputs will cause the device to become even larger, as the focal spot displacement  $\Delta y$  in (5) must be bigger to obtain a certain channel spacing  $\Delta\lambda$ , which requires a larger focal length.

In a previous design we used a conservative configuration of the receiver plane, i.e.,  $6 \mu\text{m}$  wide multimode waveguides for a large flatness region and  $3 \mu\text{m}$  wide gaps for low crosstalk between channels [12]. This, in combination with the small channel spacing necessary to fit 4 channels in one FSR resulted in a device of  $2.2 \times 3.4 \text{ mm}^2$  excluding input/output waveguides.

In the present design, an optimal balance was sought between device size on the one hand, and crosstalk and flatness region on the other. To preclude high crosstalk due to peaks from different channels becoming too close, a gap of  $2.5 \mu\text{m}$  was chosen in the receiver plane.  $4.5 \mu\text{m}$  wide multimode output waveguides were chosen to guarantee a reasonable wavelength range over which the response is flattened.

From (12) it follows that the device should work in 327th order (for TE, 326th order for TM). According to (4) and (5) and  $\Delta y = (4.5 + 2.5) \mu\text{m}$  the focal length  $f$  should be  $210 \mu\text{m}$ . ( $d = 3 \mu\text{m}$  in our design.) From the diffraction angle of the input field entering the first radiative coupler, the number of array waveguides needed to catch virtually all of the diffracted light can now be deduced. In our case this was 30.

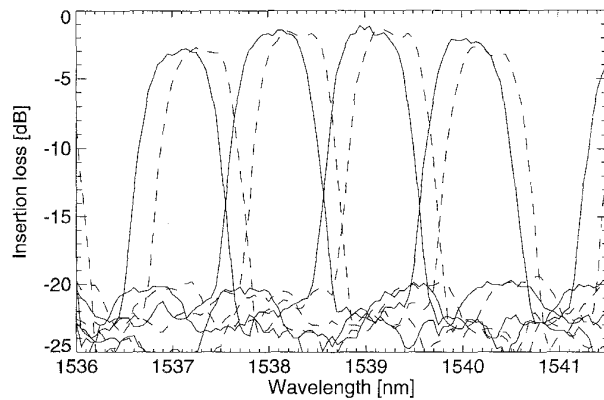


Fig. 5. Response of each of the four output channels for TE (solid) and TM (dashed). Insertion loss is 1.5 to 3 dB, crosstalk is  $-17$  dB (worst case). There is 0.2 nm of polarization independent flattened response per channel. The adjacent orders can just be discerned on both sides.

The final device design was made with the procedure described in [7], resulting in a device of  $2 \times 2.7\text{mm}^2$ .

#### VII. FABRICATION

The device was fabricated in a simple one step masking/etching process on a SI-InP substrate on which 600 nm of InGaAsP(1.3) and 300 nm of InP were grown with MOVPE [13]. It was first patterned in a 140 nm thick RF-sputtered  $\text{SiO}_2$  masking layer and then etched 350 nm with an optimized RIE etching/descumming process [14], yielding a waveguide structure as given in Fig. 2. Finally, it was cleaved and anti-reflection coated by evaporation of suitable  $\text{Si}_x\text{O}_y$  layers onto its facets.

#### VIII. EXPERIMENTAL RESULTS

The chip was measured by launching linearly polarized light from a single-mode source into the waveguides with an AR-coated microscope objective. The output light was picked up with a similar microscope objective and projected onto a Ge-detector.

The propagation loss of straight reference waveguides was measured to be  $2.0 \pm 0.2$  dB/cm for both polarizations, as determined by Fabry-Perot contrast ratio measurements of the yet uncoated sample.

The demultiplexer response was measured by exciting the device in the central input channel. The results are plotted in Fig. 5. The TM peaks are shifted 0.2 nm to longer wavelengths relative to the TE peaks, indicating a TE-TM shift 0.2 nm smaller than the calculated 4.7 nm. The response is flattened over 0.5 nm, yielding almost 0.3 nm of polarization independent flattened response for each channel. The insertion loss is 1.5 dB for the inner channels and 3 dB for the outer channels, relative to a straight waveguide. The crosstalk is  $-17$  (worst case) to  $-19$  dB.

Fig. 6(a) compares the response of one channel with what is theoretically expected, i.e., the field of a monomode input waveguide sweeping across a multimode output waveguide. Agreement is excellent, indicating that phase transfer through the array and the focus in the receiver plane are good.

In the same figure, the response of the presently considered device is compared with that of the previous design mentioned

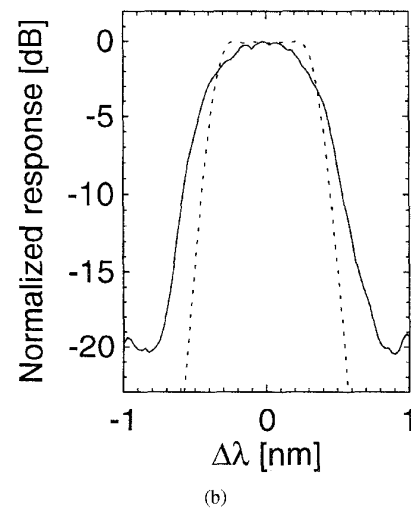
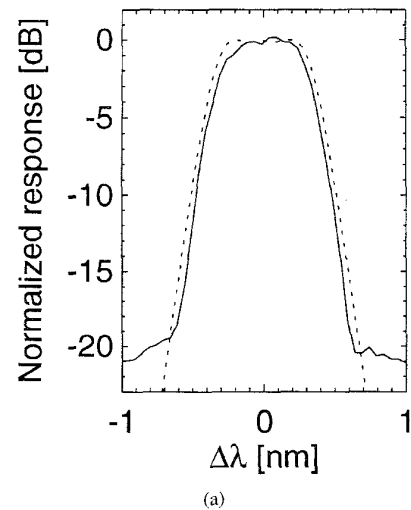


Fig. 6. (a) Simulated (modal overlap, dotted) and measured (solid) response for one channel (#2, TE). Excellent agreement indicates good focus and phase transfer through the array. Far from the peak wavelength transmission through the substrate (among other things) contributes more than the overlap between focal spot and output guide modes, hence the discrepancies seen there. (b) Response of previous device [12] compared to its simulation.

above [12]. It is seen that the new optimized device considerably improves the flatness of the response. Besides that, the maximum insertion loss is reduced from 5 to 3 dB for all channels.

#### IX. CONCLUSION

It has been shown that fabrication of polarization independent phased arrays is feasible with practical fabrication tolerances by using a flattened response, which counterbalances variations in the TE-TM shift. A four-channel wavelength demultiplexer has been made in InGaAsP/InP with a central wavelength of 1539 nm and a channel spacing of 1 nm. This has been done without requiring new technology and with very simple one step waveguide processing. The insertion loss of the device is 1.5 dB for the inner channels and 3 dB for the outer channels, which we believe to be the lowest insertion loss reported for a polarization independent demultiplexer on InP.

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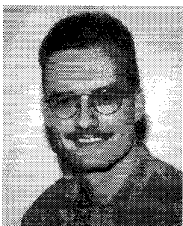


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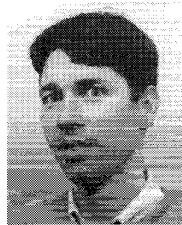
After graduating, he worked as a precision engineer at the mechanical workshop of the Delft University of Technology. In 1986, he joined the Integrated Optics group of the Laboratory for Telecommunication and Remote Sensing Technology, where he is now a process technologist in charge of optical lithography.



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Dr. Smit is a member of IEEE/LEOS and the Netherlands Electronics and Radio Society (NERG).