

# Novel InP-based phased-array wavelength demultiplexer using a generalized MMI-MZI configuration

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# NOVEL InP-BASED PHASED-ARRAY WAVELENGTH DEMULTIPLEXER USING A GENERALIZED MMI-MZI CONFIGURATION

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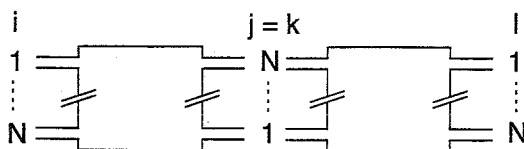
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## Abstract

A novel type of wavelength demultiplexer is presented based on a generalized MMI-MZI configuration. This device combines the potential of low loss and high uniformity of the output channels with a small device size. Feasibility of the novel concept is demonstrated experimentally for a 4-channel demultiplexer with 4 nm channel spacing. Dimensions are 2800x106  $\mu\text{m}$ , which is the smallest device size reported so far.

## Introduction

Wavelength Division Multiplexing (WDM) is an effective way to exploit the huge bandwidth of optical fibres. In this paper a novel type of wavelength demultiplexer is presented. This device employs Multi Mode Interference (MMI) couplers in a Mach-Zehnder Interferometer (MZI) configuration. Due to the application of MMI-couplers the demultiplexer has the potential of low-loss and high uniformity of the output channels.



**Figure 1.** Configuration of a MMI-MZI demultiplexer.

## Operation principle

Figure 1 shows a generalized  $N \times N$  MMI-MZI configuration. The first MMI-coupler acts as a 1 to  $N$  power splitter if the length  $L_{\text{MMI}}$  is properly chosen:  $L_{\text{MMI}} = 3L_{\pi}/N$ , with  $L_{\pi} = \pi/(\beta_0 - \beta_1)$ , in which  $\beta_0$  and  $\beta_1$  are the propagation constants of the fundamental and the first order mode, respectively. Using input  $i = 1$ , simple equations can be obtained for the phase transfer  $\phi_{ij}$  from port  $i$  to port  $j$  [1]:

1. Now works with Microtechnology Systems Group, Swiss Federal Institute of Technology, Lausanne, Switzerland.

$$\varphi_{ij} = \varphi_j = \begin{cases} \varphi_0 + \pi + \frac{\pi}{4N}(j-1)(2N-j+1) & j \text{ odd} \\ \varphi_0 + \frac{\pi}{4N}j(2N-j) & j \text{ even} \end{cases} \quad (1)$$

Travelling in the opposite direction, due to reciprocity light will constructively interfere into output 1 of the second MMI-coupler, if the phase relations of Eq. 1, with a minus sign, are satisfied, i.e.  $\varphi_k = -\varphi_j$ . For the demultiplexer transfer the phase differences  $\Delta\varphi_k = -(\varphi_{k+1} - \varphi_1)$  between the inputs of the second MMI-coupler are important, not the absolute phases.

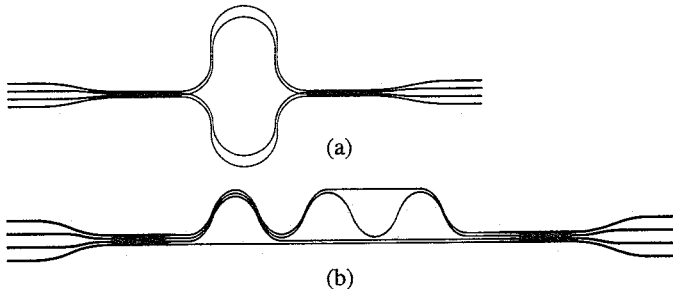
	l = 1	l = 2	l = 3	l = 4	$\Delta\varphi_k$
$\Delta\varphi_1$	$\pi/4$	$-\pi/4$	$-5\pi/4$	$5\pi/4$	$-\pi/2$
$\Delta\varphi_2$	$5\pi/4$	$-\pi/4$	$-5\pi/4$	$\pi/4$	$-3\pi/2$
$\Delta\varphi_3$	0	$\pi$	$-\pi$	0	$-\pi$
	$\lambda_1$	$\lambda_2$	$\lambda_4$	$\lambda_3$	

**Table 1.** The required phase differences between the inputs of the second MMI-coupler.

Columns  $l = 1$  to  $l = 4$  from table 1 show the differences  $\Delta\varphi_k$  which are required in order to couple all the power to output  $l$  of a  $4 \times 4$  demultiplexer. Inspection of the table shows that going from output  $l = 1$  to  $l = 2$ , from 2 to 4, from 4 to 3, and from 3 to 1 the required phase difference  $\Delta\varphi_1$  increases with a constant amount  $\Delta\varphi_1 = -\pi/2$ . The same holds for  $\Delta\varphi_2$  and  $\Delta\varphi_3$ , the corresponding values of  $\Delta\varphi_k$  are listed in the last column. From this column it is seen that if we connect ports  $j$  and  $k$  by branches with lengths  $L_k$  which satisfy:

$$\Delta L_k = L_{k+1} - L_1 = \frac{\Delta\varphi_k}{\Delta\beta}, \Delta\varphi_k = -k\frac{\pi}{2} \quad (2)$$

in which  $\Delta\beta$  is the channel spacing  $\Delta\beta = \beta(\lambda_{i+1}) - \beta(\lambda_i)$ , then the light will shift from output  $l = i$  to  $l = i+1$  if the wavelength changes from  $\lambda_i$  to  $\lambda_{i+1}$  according to the sequence listed in the last row of table 1.



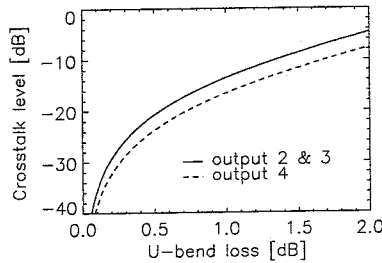
**Figure 2.** Layout of a  $4 \times 4$  MMI-MZI demultiplexer: a) conventional, and b) with U-bend sections.

It should be noted that a minor correction  $\delta L_k$  to  $\Delta L_k$  has to be made in order to satisfy the absolute phase relations at  $\lambda_1$ , which does not affect the dispersion properties, however, due to

its small magnitude. Figure 2a shows how the required length differences  $\Delta L_k$  could be realized. From the last column of the table we see that  $\Delta\phi_k$  does not monotonically increase with array guide number  $k$ , which causes crossings in the array guides. Figure 2b shows a design in which the length differences are realized by insertion of U-bends. In this design crossings are avoided.

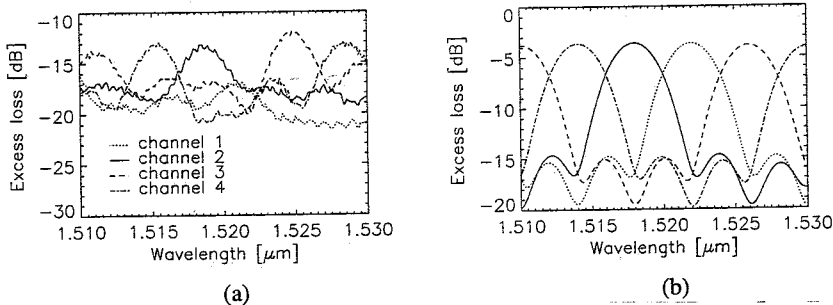
### Sensitivity to imbalance

For a proper operation of the device all signals at ports  $k$  should have proper phase and *equal* amplitude. Insertion of U-bends leads to additional losses which will be proportional to the number of U-bends inserted. If the uniformity of the signals is disturbed the imaging process will not perform properly, and power will be coupled to undesired ports leading to higher insertion loss and higher crosstalk.



**Figure 3.** Crosstalk level versus single U-bend loss.

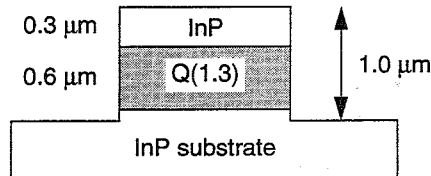
Crosstalk values can be estimated by taking into account the U-bend losses in the simulation. If the single U-bend loss is denoted  $r$ , then the amplitude at input  $k$  can be denoted as  $a_k = (1 - r)^{n_k}$ , in which  $n_k$  is the number of U-bend sections for branch  $k$ . By approximating  $a_k$  as  $1 - n_k r$ , which holds for small  $r$ , a simple equation can be derived for the resulting field amplitudes. Figure 3 shows the calculated crosstalk values. From this figure it is seen that even for losses as high as 0.5 dB per single U-bend the crosstalk is still acceptable. This is an important conclusion. It means that MMI phased-array demultiplexers are very tolerant to losses in the array branches as long as these losses depend linearly on the branch length.



**Figure 4.** Output of the realized 4x4 MMI-MZI demultiplexer: a) measured response (channel 1 defect), and b) simulated response with 1.5 dB single U-bend loss.

## Experiments

The length of the MMI sections depends quadratically on the width [2], so in order to reduce the design dimensions a deeply etched waveguide structure is used [3]. Figure 5 shows the used waveguide structure. A disadvantage of these deeply etched structures are the bend losses, which lead to a non-uniform distribution of the powers in the different array guides.



**Figure 5.** Deeply etched waveguide structure as used for the demultiplexer.

A 4x4 MMI-MZI demultiplexer has been realized in a 1.5  $\mu\text{m}$  deeply etched InP/InGaAsP/InP waveguide structure employing an etch/descum process for obtaining smooth and vertical sidewalls [4]. MMI-couplers with a width of 21  $\mu\text{m}$  and a length of 664  $\mu\text{m}$  are used, with 3  $\mu\text{m}$  wide input waveguides and with 1.4  $\mu\text{m}$  wide array waveguides. The demultiplexer was designed to operate at a central wavelength  $\lambda_c = 1520 \text{ nm}$  with 4 nm channel spacing. The total device size is 2800x106  $\mu\text{m}$  which is the smallest demultiplexer size reported so far. Figure 4a shows the measured wavelength response. The losses of the device are considerable (12 dB) due to problems in the mask, which resulted in rough waveguides. Measurements of single U-bends yielded 1.5 dB loss per single U-bend with a bending radius of 80  $\mu\text{m}$ . Although measured crosstalk values are 5 dB worse than the simulated crosstalk values (shown in Fig. 4b), demultiplexing behaviour is clearly demonstrated and qualitative agreement between simulations and experiments is good.

## Conclusion

A novel InP-based MMI-MZI demultiplexer is presented and experimentally demonstrated. Due to mask problems the realized device does not show optimal performance. The measured performance demonstrates a large tolerance to non-uniform branch losses.

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