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*Citation for published version (APA):*
Kleijn, E., Vries, de, T., Ambrosius, H. P. M. M., Smit, M. K., & Leijtens, X. J. M. (2010). MMI reflectors with free selection of reflection to transmission ratio. In J. Pozo, M. Mortensen, P. Urbach, X. Leijtens, & M. Yousefi (Eds.), *Proceedings of the 15th Annual Symposium of the IEEE Photonics Benelux Chapter, 18-19 November 2010, Delft, The Netherlands* (pp. 189-192). TNO.

*Document status and date:*
Published: 01/01/2010

*Document Version:*
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

*Please check the document version of this publication:*

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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# MMI Reflectors with Free Selection of Reflection to Transmission Ratio

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*We investigate a new class of integrated mirrors, so called MMI reflectors. In addition to one-port full reflectors, we introduce two-port MMI reflectors, capable of both reflection and transmission. The reflection to transmission ratio in these devices can be set freely by changing their geometry. This is demonstrated through numerical simulations as well as through a set of working devices realized on an indium phosphide layer stack.*

## Introduction

Reflective elements take an important place in integrated photonic circuits as essential parts in most lasers and in many filtering structures. In indium phosphide photonic ICs, broadband reflective elements are conventionally formed by cleaved facets of the semiconductor or by deep etched Distributed Bragg Reflectors (DBR).

Deep etched DBRs are strong gratings, which only need several periods for high reflectivity, resulting in a small device ($\sim 10\mu$m). They can be placed anywhere on the chip and have broadband responses[1]. However, integrating deep etched DBRs with other components adds complicated processing steps to the fabrication procedure[2].

Using cleaved facets as a reflector has a number of drawbacks. A facet has a fixed position at the edge of the chip. To obtain the desired reflectivity the facet must be coated. This means there are only two different reflectivity values per chip: the left facet reflectivity and the right facet reflectivity.

The 1-port MMI reflector, shown in figure 1a, was recently introduced[3]. It has in principle low loss ($\approx 0.1$dB) and little wavelength and polarization dependence. The device is based on a $1\times2$ MMI, but features two 45° mirrors instead of output waveguides. For a large range of materials total internal reflection will occur at the mirrors and light will be imaged back on the input waveguide. Here we present 2-port MMI reflectors, shown in figure 1b, with a freely selectable reflection to transmission ratio. The reflection coefficient of this new type of MMI reflectors is set at design time and is determined by geometry. Just like DBRs the MMI reflectors can be placed anywhere on the chip and the transmitted light is still available on chip. The main advantage of MMI reflectors over DBRs is in their ease of fabrication. Because the MMI reflectors are defined during the deep waveguide lithography and etch steps they require no extra processing steps.

## Concept

In $1\times2$ MMIs two self-images will appear at the output side[4], as shown in figure 2a. In the device of figure 1a two deep-etched 45 degree mirrors have been placed in such a way that these images will be reflected towards the MMI axis[3]. The resulting field is shown in figure 2b. The light will continue to propagate and the second mirror it encounters

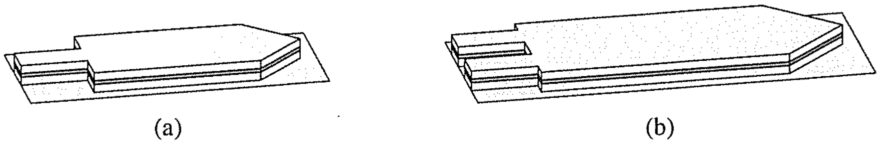


Figure 1: Schematic 3D view of (a): a 1-port MMI reflector and (b): a 2-port MMI reflector. The core layer, shown in dark grey, is sandwiched between the cladding and the substrate, shown in light grey. To obtain highly reflective mirrors the device has to be deep-etched.

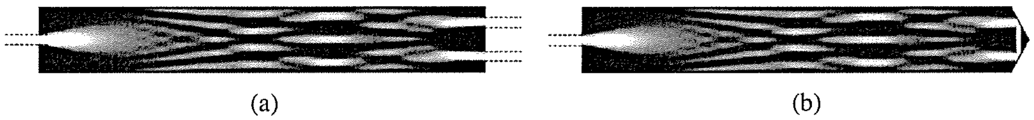


Figure 2: Field distributions in (a): the original $1 \times 2$ MMI and (b): the MMI reflector after introduction of two 45° mirrors. From [3].

will reflect it back to the input. Reflection losses at the mirrors will be very low as long as the critical angle for total internal reflection is sufficiently below 45 degrees. This is the case in both semiconductor and silica-based materials, allowing for a wide range of waveguiding materials.

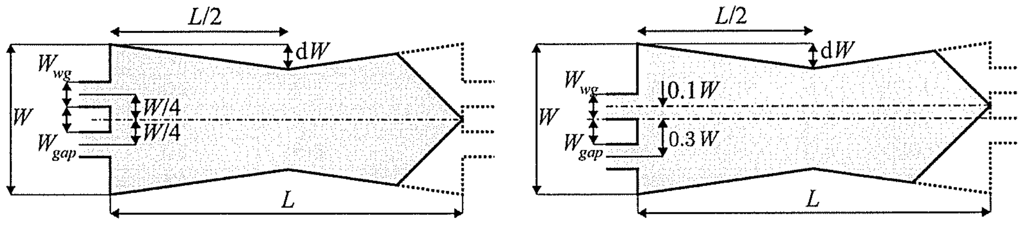
By using a $2\times2$ MMI power splitter as a basis a 2-port MMI reflector is obtained, as shown in figure 1b. The two ports can be identified as a reflection and as a transmission port. The reflection port is used as both an input and as an output, whereas the transmission port is only used as an output. It is useful in various applications to be able to set the ratio of the intensities of light exiting the reflection port and light exiting the transmission port. This ratio is defined as the power coming out of the reflection port divided by the sum of the power coming out of both ports. We will refer to this ratio as the reflection to transmission ratio. To obtain an arbitrary reflection to transmission ratio a so called butterfly MMI must be used as the basis for the MMI reflector.

Butterfly MMIs allow a free choice of the split ratio in $2\times2$ MMIs by tapering the MMI sections[5, 6]. The amount of tapering is denoted by $dW$ and can be normalized by dividing it by the base device width $W$. The tapering can be such that the centre width of the device is reduced or increased. This is indicated by the sign of $dW$, where a negative sign indicates a device that is narrower in the middle. Applying this principle to 2-port MMI reflectors results in devices of which the reflection to transmission ratio can be controlled continuously through $dW$.

In this article we will only consider MMI reflectors based on the symmetric and antisymmetric butterfly MMI devices, referred to by Besse[5] as **C** and **D**, respectively. Their geometries are shown in figure 3. The length of the reflector devices is the same as the original MMIs they are based on.

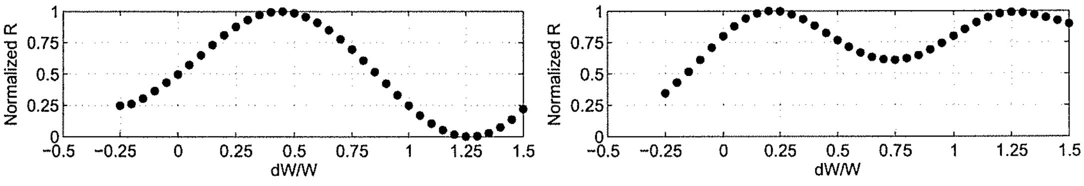
## Simulations

There are not many simulations methods that can handle reflections off non-perpendicular interfaces efficiently in relatively large structures ($\sim 50\ldots250\mu$m). When only general device parameters are of interest, such as optimum device length or reflection to transmis-



(a) **C** type butterfly MMI reflector (b) **D** type butterfly MMI reflector

Figure 3: Geometry of both types of butterfly MMI reflectors. The **C** type reflector device is symmetrical while the **D** type reflector device is asymmetrical. The original butterfly MMIs are shown as the dotted shape. The new butterfly MMI reflectors are shown as the filled shape. The position of the mirror tip is always in the centre of where the former output waveguides of the corresponding original $2\times2$ MMI used to be. Note that the tapering is not necessarily inwards, but that the devices may also be wider in the middle than the base width $W$.



(a) **C** type (b) **D** type

Figure 4: Normalized reflection coefficient as function of the butterfly parameter $\mathrm{d}W/W$ for **C** (left) and **D** (right) type devices.

sion ratio, then it is possible to create an equivalent structure that can be simulated more efficiently. This structure is changed so that the light only propagates in only one general direction. A Beam Propagation Method (BPM) can be used to examine the behaviour of this equivalent structure. The influence of the normalized butterfly parameter $\mathrm{d}W/W$ was investigated using this method. The results are shown in figure 4. The depicted reflection coefficients have been normalized according to the following equation, where $P_\mathrm{R}$ and $P_\mathrm{T}$ are the light powers coming out of the reflection and transmission ports respectively.

$$R_\mathrm{norm} = \frac{P_\mathrm{R}}{P_\mathrm{R} + P_\mathrm{T}}$$

## Results

A total of 7 type **C** devices and a total of 5 type **D** devices were designed and fabricated in the InP JePPIX process of the COBRA institute in Eindhoven. All structures were created in a single etch step by inductively coupled plasma (ICP) etching. Their reflection coefficients were chosen in such a way to cover the range $[5\%, 95\%]$, as shown in table 1. The reflection and transmission coefficients of the designs were measured separately on different device instances. Table 1 list the measured coefficients in the $R$ and $T$ columns. The losses were calculated as $-10\log_{10}(R+T)$. It becomes clear that these measured losses are much higher than the expected losses based on simulations, which are very low for most devices. We have identified the following loss sources: a non-zero sidewall

| ID | d$W/W$ | $W$ [$\mu$m] | $L$ [$\mu$m] | Meas. $R$ [%] | Meas. $T$ [%] | Simulated Loss [dB] | Measured Loss [dB] | Design $R_{\text{norm}}$ [%] | Measured $R_{\text{norm}}$ [%] |
|---|---|---|---|---|---|---|---|---|---|
| A | 1.187 | 6.0 | 252.7 | 6.3 | - | 0.7 | - | 5 | - |
| B | -0.179 | 6.0 | 51.0 | 5.6 | 10.8 | 1.5 | 7.9 | 20 | 34 |
| C | -0.085 | 6.0 | 65.4 | 10.0 | 13.0 | 0.2 | 6.4 | 35 | 43 |
| D | 0.000 | 6.0 | 78.4 | 12.6 | 9.5 | 0.1 | 6.6 | 50 | 57 |
| E | 0.085 | 6.0 | 90.7 | 18.0 | 8.7 | 0.2 | 5.7 | 65 | 67 |
| F | 0.179 | 6.0 | 105.1 | 26.4 | 4.2 | 0.3 | 5.1 | 80 | 86 |
| G | 0.312 | 6.0 | 124.6 | 32.0 | 1.5 | 0.4 | 4.7 | 95 | 96 |
| H | -0.250 | 7.5 | 48.2 | 6.5 | 10.9 | 1.0 | 7.6 | 30 | 37 |
| I | -0.150 | 7.5 | 67.8 | 12.2 | 13.8 | 0.4 | 5.9 | 50 | 47 |
| J | -0.083 | 7.5 | 80.8 | 19.0 | 6.7 | 0.3 | 5.9 | 65 | 74 |
| K | 0.000 | 7.5 | 96.8 | 23.8 | 4.0 | 0.2 | 5.6 | 80 | 86 |
| L | 0.070 | 7.5 | 110.3 | 27.6 | 1.9 | 0.1 | 5.3 | 90 | 94 |

Table 1: Design parameters and measurement results

angle (measured to be 3°), a deviation of the guiding film thickness (580nm vs 500nm), fabrication imperfections in the device width and mirror surface roughness. We estimate the losses from the first three sources to be maximally 1.2dB, 2dB and 2dB respectively. All of these losses can be reduced by improving fabrication. Table 1 also shows that the measured reflection to transmission ratio matches quite well with the design value. A quality measure is the absolute deviation between the design $R_{\text{norm}}$ and the measured $R_{\text{norm}}$. Only device B has a deviation of more than 10%.

## Conclusion

MMI reflectors with free selection of reflection and transmission ratios have been demonstrated to work. Experiments show that the reflection to transmission ratio of the realized devices matches the design value quite well. The devices show losses of 5dB to 8dB, which is much higher than expected based on simulations. Around 5dB of these losses can be attributed to fabrication related issues. We are currently working on reducing these losses. This will make the presented MMI reflectors good alternatives to deep etched DBRs.

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