# MMI-Reflector: A Novel On-chip Reflector for Photonic Integrated Circuits

L. Xu, X.J.M. Leijtens, B. Docter, T. de Vries, E. Smalbrugge, F. Karouta and M.K. Smit

COBRA research institute, Eindhoven University of Technology, P.O. Box 513, 5600 MB The Netherlands
✉ X.J.M.Leijtens@tue.nl

***Abstract*** *We present a novel, compact, on-chip multi-mode interference (MMI) reflector, with near-100% theoretical reflection. We measured 78±10% reflection for an InP-based MMI-reflector fabricated with a single etch step with inductively coupled plasma (ICP) etching technique.*

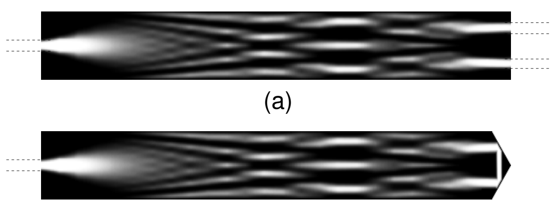
## Introduction

In photonic integrated circuits (PICs), a mirror is often needed for reflecting light or for forming a (laser) cavity. Typical reflectors that are used are the cleaved facet of the semiconductor material, possibly provided with a high-reflectivity (HR) coating, or on-chip distributed Bragg reflector (DBR) gratings[1,2]. In theory, both solutions can provide close to 100% reflectivity[3,4], and the reflectivity can be chosen flexibly, by applying a proper coating to the facet, or by choosing the number of grating periods. The disadvantage of using the cleaved facet is that the location of the mirror cannot be freely chosen, but is determined by the circuit and sample geometry. Components in the PIC needing the reflector have to be extended to the facet, which limits the design flexibility. For the sub-micrometer DBR gratings, the fabrication is challenging, and when integrating the gratings with other photonic components, they add additional complexity to the fabrication procedures[2].

In this paper, we introduce a novel on-chip reflector, the MMI-reflector, which achieves high reflectivity with a single waveguide etch step and which can be flexibly positioned anywhere in the circuit. As an added advantage, when used in a laser cavity, such reflectors enable on-wafer testing without the need of first cleaving the sample. The device is based on a 1×2 3-dB multimode interference (MMI) coupler, where the two output waveguides have been replaced with two 45° etched mirrors. We measured 78±10% reflectivity for MMI-reflectors fabricated with an inductively coupled plasma (ICP) etching technique.

## Concept and design

The principle of operation of the MMI reflector is illustrated in Fig. 1. The device works as follows: (a) The light enters the 1×2 MMI power splitter, which, at a certain length ($L_{\mathrm{MMI}}$) will image the input onto two light spots[5]. (b) When two 45° mirrors are placed close to the position of these focal points as indicated in the figure, the light will be reflected (turn by 90°), and will focus on the central axis of the MMI instead. The light will continue to propagate and is reflected by the second mirror back through the MMI to be focused on the input waveguide. For semiconductor materials the mirror angle of 45° is well below the critical angle, which is around 70°, and hence the light will experience total internal reflection. For silica-based materials, the 45° is still slightly below the critical angle so this concept will be applicable for a large range of waveguiding materials.



(a)

(b)

**Fig. 1:** Principle of operation: (a) a beam propagation simulation of a 2×2 MMI power splitter. (b) By properly positioning the output 45° mirrors, the light is reflected back to the input waveguide.

It is important to notice that no light is focused at the corners of the reflecting facets, that will typically show some rounding due to the limited fabrication resolution. For additional tolerance, we avoid rounding of the mirror facets close to the outer corners, by extending them as shown in the right side of Fig 2. In addition, possible unwanted reflections from the input facet of the MMI are reduced by using angled corners, see the left side of the Fig. 2[6].

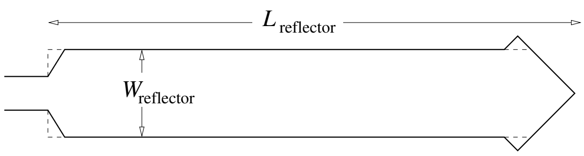



**Fig. 2:** Annotated mask layout of the MMI reflector.

We designed and fabricated an MMI-reflector. It uses a 500 nm InGaAsP film ($\lambda_{gap} = 1.25\,\mu$m) on an InP substrate with a 1500 nm InP top cladding. The 1×2 MMI-reflector is designed 6 $\mu$m wide ($W_{\mathrm{MMI}}$) and 37.86 $\mu$m long ($L_{\mathrm{MMI}}$), and it has a 2 $\mu$m wide access waveguide. The mask layout of this MMI reflector is shown in Fig. 2, drawn to scale.

All circuits were fabricated by etching with an inductively coupled plasma (ICP) technique using a $Cl_2$:Ar:$H_2$ chemistry[7]. The waveguide structures and the mirrors were etched simultaneously. A SEM picture of a deeply etched waveguide etched with ICP is shown in Fig. 3.

The reflectivity of the MMI reflector depends on the etched waveguide sidewall angle. Simulation results[8],

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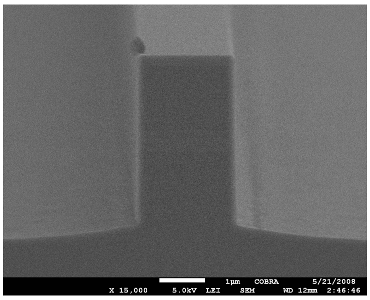


**Fig. 3:** A SEM photo of a deeply etched waveguide by ICP etching with almost vertical side wall.

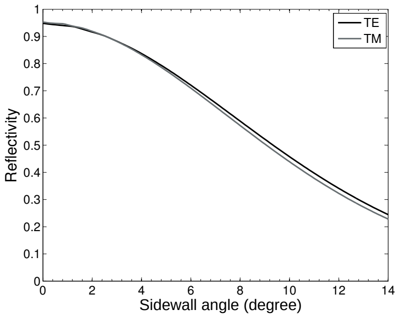


**Fig. 4:** Simulated influence of the sidewall angle on the reflectivity of a single reflection at 45° incidence.

in Fig. 4, show that the reflectivity drops from 95% to 60% when the angle increases from vertical (0°) to 7°. The MMI reflector has weak wavelength and polarization dependence. Simulation shows that the reflectivity variation within a 60 nm range (1520 nm–1580 nm) can be as small as 0.07 dB (1.6% deviation). For the polarization dependence of the reflectivity we find 0.07 dB as well.

## Characterization

It is difficult to measure the reflectivity of the MMI reflector directly. Therefore we have designed some circuits to facilitate the reflectivity calibration, shown in Fig. 5,in which one of the 2×2 3-dB MMI access waveguides is guided to the other side of the chip for convenience of measurement. The straight waveguide (b) and the straight waveguides with curves (c) are used to calibrate the loss of the extra waveguide to port 3. The reflectivity of the MMI reflector can be calculated through

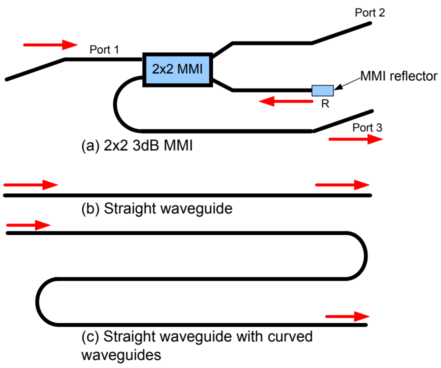


**Fig. 5:** The devices used to calibrate the reflectivity of the MMI reflector.

equation

$$R_{\mathrm{dB}} = -10\log\left(\frac{P_{\mathrm{port2}}}{P_{\mathrm{port3}}}\right) + \alpha_{\mathrm{extra}} + \alpha_{\mathrm{MMI}} + 3$$

in which $P_{\mathrm{port2,3}}$ are the output optical powers at port 2 and port 3, $\alpha_{\mathrm{extra}}$ is the loss of the extra waveguide, $\alpha_{\mathrm{MMI}}$ is the insertion loss of the MMI and the extra 3 dB accounts for passing the MMI a second time.

The extracted excess loss of the 3 dB 2×2 MMI is about 1 dB, and the loss of the extra waveguide is extracted to be about 1.9 dB±0.5 dB. The power imbalance between port 2 and port 3 is 7 dB. The reflectivity of the MMI reflector is then calculated to be 78%±10% (−1.1 dB±0.5 dB).

## Conclusion

We have proposed and demonstrated a novel on-chip reflector, the MMI-reflector, which achieves high reflectivity of 78%±10%. It can be used, for example, as an alternative to cleaved facets with HR coating or to DBR gratings in photonic integrated circuits. The fabrication procedure involves only a single deep etch step, which could be used for the realization of other waveguide components at the same time. The device can be located at any position and oriented in any direction, and therefore it offers great flexibility in the design of photonic integrated circuits.

## Acknowledgements

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