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Experimental Assessment of the Reflection of Passive Multimode Interference Couplers

D. Erasme, L. H. Spiekman, C. G. P. Herben, M. K. Smit, Member, IEEE, and F. H. Groen

Abstract—Integration of semiconductor amplifiers in integrated optical circuits is presently possible. Reflections inside these circuits are undesired for they can cause unwanted oscillations. The reflection properties of integrated passive multimode interference (MMI)-couplers have been experimentally determined.

Index Terms—Integrated optics, multimode interference (MMI) coupler, reflectometry, semiconductor waveguides.

I. INTRODUCTION

Recent advances in integrated optics technology have allowed for the insertion of optical amplifiers in semiconductor integrated optical circuits [1], [2]. With integrated amplifiers, local reflections occurring within the optical circuits become an important issue since they will result in an oscillating behavior of the response. Particularly, multimode interference (MMI)-couplers that are intensively used in integrated optics devices can be expected to provide reflections since they contain abrupt junctions. The issue of MMI-coupler reflections in semiconductor lasers was addressed by Pennings et al. [3]. The paper concentrates on the occurrence of resonant modes in the coupler. The present work is concerned with the assessment of the reflections of passive MMI-couplers, including nonresonant conditions. The experimental results are compared with the simulated data from [3].

II. APPROXIMATE ANALYSIS

As pointed out by Pennings et al., the issue of the reflection of MMI-couplers has two different aspects, one concerning back reflections into the input waveguide and the other concerning resonant modes within the MMI-coupler.

In this letter, an approximate analysis and an experimental investigation of the actual reflection coefficient of an MMI-coupler structure is presented. Two operating regimes of the MMI-coupler can be distinguished. The first one consists in designs where full transmission from the input to the output ports occurs. For this case the residual reflection coefficient is measured for the optimum design and the deviation from those values due to fabrication tolerance. The second case corresponds to designs in which the MMI-coupler is used for suppressing part or all of the input light as for a Mach–Zehnder recombiner in the case of out of phase inputs. In that case, part of the image of the inputs is formed onto the endface of the MMI-coupler. One can expect that this type of design is subject to a rather high level of reflection; it should be avoided in structures using amplifiers. We have studied this case via the measurement of MMI-couplers in which all exit waveguides have been omitted.

III. MEASUREMENT PRINCIPLE

The difficulty in measuring on chip reflections lies in the identification of the various sources of reflection. For example, the device input and output facets generate reflections as well as the splitter required in order to separate the input beam from the reflected one. Techniques that are able to distinguish in the various sources of reflection such as time-domain or low-coherence interferometric reflectometry [4], [5] require a complex measurement setup. In order to obtain a simple technique for measuring reflections in MMI-couplers, using standard transmission measurement equipment, a Michelson interferometric structure has been integrated with the optical test circuit itself. A reference reflecting edge is used in order to determine the position of the reflection detected. The measurement structure works as follows: the light launched into the input port is split into two equal parts by a 3-dB MMI-splitter. One part is transmitted to the reference reflecting edge whereas the other one is launched into a guide leading to the MMICoupler-under-test. The backward propagating light beams interfere in the exit guide and are measured at its output. The interference pattern between the different reflecting beams is measured by sweeping the wavelength of the input beam over a few nanometers. This is obtained by thermal tuning of a DFB semiconductor laser source. Disturbing reflections at the chip endfaces are reduced by antireflection coatings.

Assuming the reference reflector and the MMI-coupler under test are the only sources of reflection the light intensity measured at the output of the waveguide can be analyzed as follows. After the splitting in the 3-dB MMI-splitter and the attenuation in the guides, a part \( \alpha P \) of the power \( P \) reaches the entrance of the MMI-coupler-under-test. It is partially reflected with a reflection coefficient \( R_{\text{test}} \). Of the reflected power \( R_{\text{test}} \alpha P \), a fraction \( \alpha' \) reaches the end of the output guide. Another fraction \( \beta \) of the input power reaches the edge used as a reference reflector, is reflected there with coefficient \( R_{\text{ref}} \) and...
reaches the output: \( \beta \beta' R_{\text{ref}} P \). The two light beams interfere in the output waveguide leading to a measured intensity equal to
\[ P_{\text{total}} = \alpha \beta' R_{\text{ref}} P + \beta^2 R_{\text{ref}} P \]
\[ + 2P \left( \sqrt{\alpha \beta' R_{\text{ref}} \beta' R_{\text{ref}}} \right) \cos \left( \frac{2n_{\text{eff}} \pi}{\lambda} \delta L \right) \]  
(1)
where the product \( n_{\text{eff}} \delta L \) is the optical path length difference (\( \delta L = 2 \times 1.4 \text{ mm} \)) and \( \lambda \) is the wavelength of the input beam. Some test structures are added on the mask in order to determine the losses occurring in the straight waveguides, the curved waveguides and the 3-dB coupler. From these measurements the coefficient \( \alpha' \), \( \beta' \), and \( \lambda' \) are determined. The sweeping of \( \lambda' \) results in oscillations of the measured output intensity which allow for the derivation of \( R_{\text{ref}} \) and \( R_{\text{test}} \) after comparison with the transmission of the straight reference waveguides. In order to reject fast fluctuations a numerical low pass filtering is applied to the data.

All other residual reflections also lead to oscillations. With this geometry, the beating between the reference reflection and any reflection localized around the splitting MMI-coupler is eliminated since the path length difference is too small to generate wavelength dependence. Eventually, those reflections contribute to \( R_{\text{ref}} \). The sensitivity limit occurs when the oscillations to be measured are hidden by those created by the beating of the input and output facet reflections with the reference one.

### IV. DEVICE CHARACTERISTICS

The waveguides on the samples are deeply etched waveguides. This corresponds to the worst case for reflections since a large fraction of the light in a propagation mode will “see” the semiconductor/air discontinuity at the end of a waveguiding section. Two chips have been fabricated. Both chips were fabricated in an MOVPE grown InP–InGaAsP(Q1.3)–InP layer stack, with a 600-nm film layer and a 300-nm top layer. For chip 1, a 30-nm-thick PECVD-SiN\(_x\) layer served as an etching mask for the waveguides. The pattern was defined using projection UV-exposure with negative photoresist and transferred in the SiN\(_x\)-layer by CHF\(_3\) reactive ion etching. The waveguides were etched using a CH\(_4\)/H\(_2\) etching process. This resulted in almost vertical sides (4\(^\circ\)). The second chip had a 100-nm-thick PECVD-SiN\(_x\) layer as etching mask for the waveguides that were etched employing an optimized CH\(_4\)/H\(_2\) etching and O\(_2\) descumming process [6]. This resulted in tilted sides (10\(^\circ\)).

All the waveguides are 1.4-\( \mu \text{m} \) wide and single-mode in order to avoid intermode interference. The access waveguides to the MMI-couplers are tapered up to 2.2 \( \mu \text{m} \) to make the

### V. EXPERIMENTAL RESULTS

The input circuits (first 3-dB coupler) of all four series are identical. The measurement of \( R_{\text{ref}} \) gives some information on the repeatability of the reflection. The measured average value of \( R_{\text{ref}} \) is generally close to \(-18 \text{ dB} \) and the standard deviation is between 2 and 3 dB (see Table I).

The variations are caused by difference between the two samples, the position of the series in a single sample and the polarization. The reflection is strongly affected by the quality of the edge and can vary from structure to structure. Figs. 1–4 show the variation with MMI-couplers length of \( R_{\text{ref}} \) for the series where the exit guides have been omitted. It appears that the reflection for a MMI-coupler in the worst (unrealistic)
condition (there is no reason for omitting the exit waveguides in a real case) would be below $-20$ to $-25$ dB. These values agree with the calculated coefficient of Pennings ($-22$ dB). The difference observed between the reference reflections and the MMI-coupler total reflections accounts for the MMI-coupler transmission losses that are excluded in the reference reflections through calibration and counted twice in the total reflections.

For the series with exit waveguide, it is noticed that the reflection is expected to be below the sensitivity of our measurement method. Parasitic oscillations will mask the beating between the reference and the MMI-coupler-under-test reflected beam. A few cases (7 out of 48) were measurable giving results between $-40$ and $-45$ dB. All others cases are below the sensitivity. That sensitivity can be estimated from the parasitic oscillation. It is typically in the range from $-45$ to $-50$ dB (worst case $-42$ dB). The simulated MMI reflection is typically below $-50$ dB with a few worst case peaks remaining below the $-40$ dB level [3]. From the measurements it is confirmed that MMI-coupler reflections are less the $-40$ dB. In the fabrication of semiconductor amplifier chips, it is required that the antireflection (AR) coating should suppress reflections to a $-40$ to $-50$ dB level in order to avoid resonance in the gain spectrum. The present measurements show that even for a deeply etched waveguide structure the reflections from MMI-couplers would be sufficiently low for allowing integration with amplifiers. The range of MMI-coupler lengths used (22–55 $\mu$m) here is much larger than the fabrication tolerance for the device. Furthermore, the optimum MMI length being inversely proportional to the wavelength, it is interesting to notice that the relative length range 22 $\mu$m/40 $\mu$m and 55 $\mu$m/360 $\mu$m is much larger that the relative gain spectrum of a typical semiconductor amplifier (e.g., 100 nm/1550 nm). The reflection results are valid for the whole spontaneous emission spectrum. Nevertheless it appears clearly from the measurement of the series excluding exit waveguide that the MMI-coupler design should exclude situations where a large part of the light is focused onto the endface of the MMI-coupler. If this is not possible it is recommended to position a dummy exit waveguide at this position or to tilt the edge.

VI. CONCLUSION

Many future integrated optics devices will include semiconductor amplifiers for emission, optical processing, amplification or wavelength conversion as well as MMI-devices for routing and multiplexing. The reflection properties of the MMI-structures are of crucial importance in those devices since unwanted amplifier oscillations should be avoided. A measurement of the residual reflections caused by passive MMI-couplers in an integrated optical chip has been performed. The case of deeply etched waveguides has been considered as a worst case. It was found that for sidewalls $4^\circ$ off vertical the reflection at an endface of the MMI-coupler back into the input guide would be generally below $-20$ dB. This gives an upper limit for the overall reflection of MMI-coupler. In practical cases where exit waveguides exist most of the light is transmitted and the reflections fall below $-40$ to $-50$ dB. This result is rather insensitive to fabrication tolerance and amplifier wavelength range. It might be required in some special cases to design dummy exit waveguides. The values for reflection coefficients allow for the integration of amplifier and well designed MMI-couplers.

REFERENCES


