On the characterization of integrated power splitters and waveguide losses using optical frequency domain interferometry

(Student paper)

Luis A. Bru,[1] Daniel Pastor,[1] and Pascual Muñoz[1,2]
[1] *Universitat Politècnica de València, c/ Camino de Vera s/n - 46021 Valencia - Spain*
email: dpastor@dcom.upv.es
[2] *VLC Photonics S.L., c/ Camino de Vera s/n - 46021 Valencia - Spain*

ABSTRACT

In this paper, we propose a technique to characterize integrated power splitters and waveguide losses. Taking advantage of the time domain resolution of an optical frequency domain interferometry measurement, we present two versions of a test device comprising interferometers and the power splitters under test providing a mean to characterize the splitting power ratio of them and the losses of the employed integrated waveguides, in a single (or double) measurement wavelength-resolved scheme. We provide details on the model and examples of the numerical work supporting its validity. To conclude, we provide some discussion of the techinque, including the possible implementations for future experimental validation.

Keywords: optical frequency domain reflectometry, power splitter, multimode interferometer, integrated test structure, integrated waveguide losses.

1 INTRODUCTION

Optical characterization of integrated devices conforming photonic integrated circuits (PIC) is an indispensable step in the design optimization workflow. The optical spectral amplitude response of a device under test (DUT) provided by the conventional methods becomes often insufficient to evaluate the minutiae of its performance. The availability of the optical phase response, enabled by advanced characterization methods like optical frequency domain reflectometry (more correctly denoted OFDI, standing for interferometry, when used in transmission configuration [1], [2]), permits to derive the time domain response of the DUT by Fourier analysis and turns out to be extremely useful to localize unexpected contributions and fadings explaining the performance deviations from the employed model [3].

The direct characterization of more than one input and/or output device is subject to the uncertainty of optical power coupling efficiency, which typically varies from one channel to other due to chip fabrication errors and varying measurement conditions. This is the case for 2×2 and 1×2 optical power splitters or couplers (PS), of ubiquitous use in any PIC and commonly implemented by multimode interferometers (MMI) and directional couplers (DC). A straightforward strategy to approach this issue comprises the using of a cascade of the same devices having multiple outputs to be measured and fit the outcome data to a linear function [4], implying a sequence of measurements, the more the better for an accurate mean value. Here we present a technique assisted by OFDI, which explotes the strength of the time domain response of the DUT to evaluate the power splitting ratio of PSs, as well as the integrated waveguide (IW) propagation losses, wavelength-resolved in a fast single or double measurement scheme. The technique is enabled by the use of two integrated PS test device (PSTD) versions that we present in section 2, where we also show their application range on each case and some numerical validation. Afterwards, we present our discussion and conclusions, including physical implementations on the experimental work to come in section 3.

2 THE TECHNIQUE

OFDI is a well-known technique based on homodyne detection which provides both amplitude and phase, frequency and time domain resolution [1], [2]. In Fig. 1(a) a tunable laser (TL) sweep of $\Delta\lambda$ span feeds the upper interferometer, typically Mach-Zehnder type (MZI), interrogating the DUT and generating an interferogram containing amplitude and phase spectral information of the DUT, which needs to be properly resampled by the TRIG-MZI interferogram below (fulfilling Nyquist criterion for the corresponding path length differences (PLDs) by $\Delta L' \geq 2\Delta L$) to suitably run Fourier analysis on it. The time domain response of a DUT is composed of the different events taking place on it: provided that they are spatially separated, the events can be isolated and the proportionality between their contained information (position, energy, optical phase) is conserved. This feature have been demonstrated to be extremely useful to localize and identify unexpected events in integrated devices, as well as to relate optical phase and positions to characterize performance or derive propagation parameters (e.g. [5], [6]). In this work, we explote the optical power of the temporal peaks, by intentionally proposing a test structure, to characterize PS performance and IW losses.

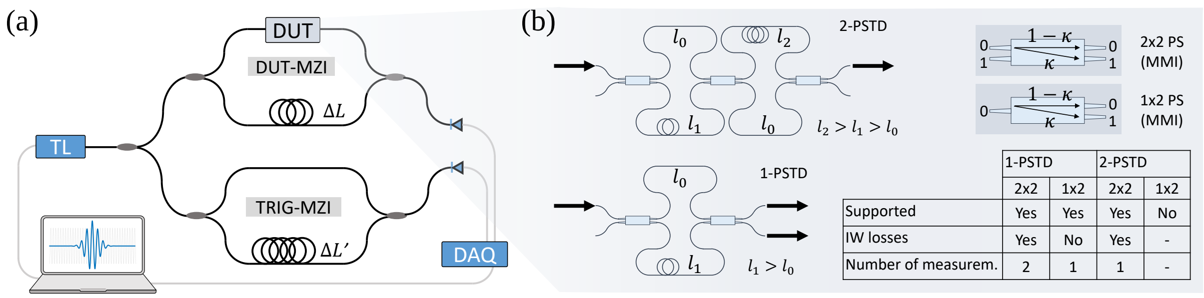

Figure 1. Sketch of an OFDI setup (a) and of the proposed PS test devices, including a summary table of their applicability in (b).

The main version of the PS test device (that we call 2-PSTD) is shown in Fig. 1(b) at the top, and comprises a serial combination of two MZIs and three PSs under test. The time domain transfer function of this structure is composed of 4 contributions corresponding to the 4 possible paths: the shortest one going through the shorter MZI arms (length $2l_0$), the next going through the arms below ($l_0 + l_1$), and so forth for the remaining 2 combinations, corresponding to lengths $l_0 + l_2$ and $l_1 + l_2$. In this way, each followed path hits the PS in a different combination of bar/cross states and IW lengths. The PS under test (see inset in Fig. 1(b)), a 2×2 type in this case, have bar (0-to-0 and 1-to-1 channels) and cross (1-to-0 and 0-to-1) connections, and it can be modeled by the following matrix $\hat{M}$:

$$\hat{M} = \gamma \begin{pmatrix} \sqrt{1-\kappa} & j\sqrt{\kappa} \\ j\sqrt{\kappa} & \sqrt{1-\kappa} \end{pmatrix}, \hat{P}_{a,b} = \begin{pmatrix} e^{-\alpha \frac{l_a}{2}} e^{-j\beta l_a} & 0 \\ 0 & e^{-\alpha \frac{l_b}{2}} e^{-j\beta l_b} \end{pmatrix}; \quad (1)$$

where γ stands for the insertion loss of the coupler and κ determines de PS power ratio. Matrix $\hat{P}_{a,b}$ describes the propagation regions in the MZIs for IW lengths l_a and l_b (being $a, b = 1, 2$ and 3), where the propagation is governed by β, and propagation losses given by α. The transfer function of the 2-PSTD is thus given by $\hat{M}\hat{P}_{2,0}\hat{M}\hat{P}_{0,1}\hat{M}$. By choosing the input field F_0 on the upper input, and by OFDI measurement of the upper output (span $\Delta\lambda$ and PLDs set to ΔL and $\Delta L'$), after some algebra it can be obtained the associated power coefficients Λ_i for $i = 1, 2, 3$ and 4 events as:

$$\Lambda_1 \propto \kappa^2 (1-\kappa) e^{-2\alpha l_0}, \Lambda_2 \propto \kappa^2 (1-\kappa) e^{-\alpha(l_0+l_1)}, \Lambda_3 \propto (1-\kappa)^3 e^{-\alpha(l_0+l_2)}, \Lambda_4 \propto \kappa^2 (1-\kappa) e^{-\alpha(l_1+l_2)}, \quad (2)$$

all of them under the same proportionality conditions. By trivial relations between them, we have a mean to obtain κ and α, so that 2-PSTD allows to characterize both magnitudes in a single-measurement scheme. Besides, OFDI can be applied piecewise to a sequence of sub-bands within the whole band, allowing to obtain the trend of $\kappa = \kappa(\lambda)$ and $\alpha = \alpha(\lambda)$ along $\Delta\lambda$. This is confirmed by numerical simulation of the measurament system: in Fig. 2(a) it is shown the time domain response of the 2-PSTD (with chosen lengths $l_0 = 2$ mm, $l_1 = 3$ mm and $l_2 = 4$ mm) after an OFDI measurement with wavelength sweep span $\Delta\lambda = 100$ nm centered at 1550 nm, and PLDs set to $\Delta L = 20$ cm and $\Delta L' = 80$ cm, describing a typical fiber-based OFDI system. Regarding the IWs, it is considered a second-order dispersion through $D = 1430$ ps nm^{-1}km^{-1} and varying propagation losses from 2.2 to 1.8 dB/cm along $\Delta\lambda$, as shown in black solid line in the corresponding inset. Similarly, the PS power ratio has been chosen to vary from $\kappa = 0.4$ to 0.55. The processing of the resulting interferograms has been performed piecewise to have 10 evenly distributed data along $\Delta\lambda$, where the distance between the contributions is more than enough to keep them away from each other after the corresponding time domain broadening of the peaks in the sub-bands. To account for this temporal broadening and the induced by IW dispersion, the coefficients Λ_i are obtained by integrating each peak independently. The recovered κ and α are plotted (blue points) in the corresponding insets, showing an almost perfect agreement with the starting parameters. The method has been verified to be robust against dispersion and different coupling conditions to 2-PSTD.

An alternative version to 2-PSTD is also considered, formed by a single MZI and two PSs as shown in Fig. 1(b) at the bottom (1-PSTD). The transfer function of this device is given by $\hat{M}\hat{P}_{0,1}\hat{M}$. As summarized in Fig. 1(b), the derived coefficients for each one of the outputs is not enough to get κ and α as in 2-PSTD: one of the measured outputs permits to obtain α, to be used as input data to obtain PS power ratio with the other. This structure is also used for the same purpose in [7], where the method is based on an analysis of the spectral response instead. We show numerical simulation of the technique using 1-PSTD in Fig. 2(b), using the same parameters as described above. In this case, we have 2 contributions in the time domain response for each case: the two ones corresponding to the upper output (solid line) and the ones for the other (dashed line). After processing under the same conditions as in 2-PSTD simulation, κ and α are obtained, showing again a perfect agreement with the designed parameters. Finally, just mention that 1-PSTD can be easily adapted to test 1×2 PSs power ratio.

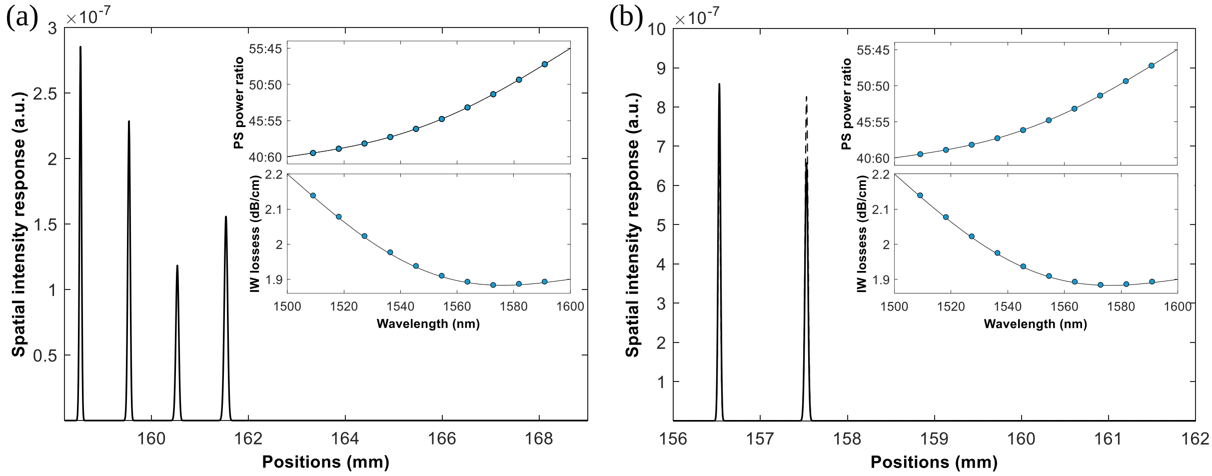

Figure 2. (a) Numerical simulation of the time domain response of the 2-PSTD. In the inset, the IW losses and PS power ratio targeted (solid line) and recoverd by the technique (dots). (b) The same plots for 1-PSTD. In the main plot, the time domain responses of both outputs are shown (solid and dashed lines).

3 DISCUSSION AND CONCLUSION

We have presented a technique to characterize PSs and IW losses by relying on OFDI. In this context, on the one hand we have proposed a more complex device (2-PSTD) allowing for single measurement, wavelength-resolved derivation of PSs power ratio and IW losses. On the other hand, a simpler version (1-PSTD) consisting of a single MZI with two PSs under test opening and closing the paths. This second device is equivalent to the used in [7] for the same purpose. However, the fact the proposed technique is based on OFDI-enabled time domain response paves the way to untangle the different contributions involved. Amongst the benefits, this allows to design a more complex structure as it is the case for 2-PSTD, enabling a single-measurement characterization, and also makes the technique robust against the presence of chromatic dispersion. Beyond, there is room to obtain other parameters such as IW dispersion [6]. Furthermore, the technique can be in principle adaptable to the integration of the OFDI structure [5], having some extra benefits as for instance, not having to depend on a bulky fiber-based setup and an intrinsic dispersion de-embedding mechanism. The proposed technique is ready to be experimentally implemented and tested in all the mentioned versions, including comparison to other existing methods to obtain IW losses and PS power ratio [4], [7], [8].

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