Novel pure-optical test-on-wafer technique based on a Point Reflector Optical Waveguide

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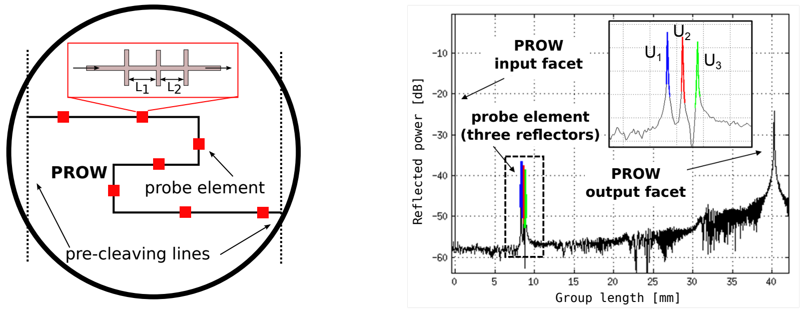
Wafer-level test approaches enabling a fast and low-cost quality assessment of the fabrication process, in terms of uniformity and repeatability, are of fundamental importance to any photonic integration foundries. In this work, we present a novel test-on-wafer technique based on a suitably engineered Point Reflector Optical Waveguide (PROW) spanning across the entire photonic wafer. The proposed technique exploits coherent optical frequency domain interferometry (OFDR) for the optical read-out of the PROW, allowing the estimation of key optical parameters of the waveguides on several points of the wafer from a single frequency domain measurement.

Introduction

It is widely recognized that in the near feature the market breakthrough for integrated optical circuits (PICs) will be closely related to the increasing of the complexity of the circuits, with new applications and business opportunities [1]. The challenge of new markets require the possibilities of high volume productions at lower costs to ensure the necessary competitiveness. The yield of the production processes will therefore be one of the key aspects for the photonic companies in the near future, as it happens in the electronics market. In this framework, the measurement of the quality at the end of a production process in term of compliance with the guaranteed specifications is a valuable instrument for the foundries. These measurements have to be done directly on wafer, before the dicing of the single cells, with a quick and cheap technique that allows evaluate few parameters descriptive of the quality of the completed process, its uniformity and repeatability. The proposed solution is based on a Point Reflector Optical Waveguide (PROW). It is a full-optical technique that allows the measurement of the optical parameters of the waveguides directly at a wafer level. With a single test, it is possible to retrieve information from several measuring points distributed across the wafer, allowing a quick sampling of the whole area. In the next sections the concept of the test technique is described and the design of the probe element is discussed.

Design and concept of optical probing

Figure 1(a) shows the proposed approach for the measurements of optical parameters throughout the wafer. As already mentioned, it is based on a Point Reflector Optical Waveguide (PROW) which consists of a long waveguide with several probe elements exploited to measure the required parameters along the waveguide. In this scheme the light is coupled in the structure via butt-coupling and the wafer has to be prepared with two cleaving (see figure 1(a)) in order to have straight facets and a good coupling coefficient on both side of the PROW. Other solutions may rely on grating-assisted vertical coupling.



(a) (b)

Figure 1: (a) Sketch of a single PROW with several probe points distributed along the waveguide. In the inset, a scheme of a single probe point. (b) An example of (simulated) data collected from a PROW with a single probe element.

An arbitrary number of PROWs can be placed on the wafer to measure the parameter in any required point but each structure has to be measured independently. Several parameters can be used to monitor the compliance of a waveguide to the specifications, including phase and group effective indices, losses, and the average backscatter generated by the sidewall roughness [2]. The technique proposed in this work focuses on group effective index and propagation losses whose values are strongly tied to the waveguide geometry.
The probe element is composed by three lumped reflective sections which form a single sensing unit. A fundamental assumption for the application of this technique is that the perturbation the reflectors produce on the parameters of propagating mode is negligible with respect to the sensitivity required to the measurement. The measurement of the PROW is done by exploiting an Optical Frequency Domain Reflectometry (OFDR) technique [2], which allows an interferometric analysis of the light reflected along a waveguide. Reflected power spectrum is collected in the spectral domain and then Fourier transformed to retrieve the data in the spatial domain. Each reflective section contributing to the total power reflected by the PROW is then identified and measured.
The main constraints to the design of a PROW are related to the total number of reflectors placed on the waveguide. Larger amount of reflectors implies also larger losses along the whole waveguide and then a reduced sensitivity for the farther elements. Depending on the involved technology, good compromise between density of the probes and total losses must be found to ensure reliably results.
An example of this kind of analysis is shown in figure 1(b), where a simulation of a $11.5mm$-long PROW with a single probe element is reported. Propagation losses of $2dB/cm$ have been assumed. Each reflector generates a lumped loss of $0.5dB$ and a reflection coefficient of $-40dB$. The physical lengths of the waveguides between the three reflectors are respectively $L_1 = 80\mu m$ and $L_2 = 79\mu m$. The graph shows the power reflected at each section of the long waveguide: the input/output facets are clearly visible as well as the three reflectors which form the sensing element (in the inset the area close to the probe). The distance of each section from the input facet is reported as group length.

Parameters extraction

In this section the extraction the group index and the propagation loss through the data collected from the PROW is shown. This processing is applied to each probe element,

resulting in a mapping of the values in the chosen points of the PROW.
The group effective index is directly calculated from the phase of each reflection measured with the OFDR technique described in the previous section. The basic assumption is that the value of the index is constant on the entire waveguide section occupied by the probe. The three reflections U_i (with $i = 1,2,3$) generated inside a single probe element posses a phase that can be defined as

$$\measuredangle U_i = \theta_i + \varphi_i = \theta_i + \beta_0 2z_i + \beta_1(\omega - \omega_0)2z_i \tag{1}$$

where θ_i is the phase of the reflector and φ_i the propagation contribution for a section placed at distance z_i inside the structure. A linear expansion of the propagation constant around the central frequency ω_0 in the form $\beta(\omega) = \omega_0 n_{eff}/c + (\partial\beta/\partial\omega)|_{\omega_0}$ has been used. The physical lengths z_i must be doubled because of the double passage inside the structure required by the measurement. We can then compute the phase difference between two adjacent reflectors inside a single triplet, which is only dependent on the two physical lengths L_1 and L_2 of the waveguide sections inside the probe unit, assuming the two reflectors add the same contribution θ_i. With a linear interpolation of the two differences we can finally estimate the linear term β_1, which is related to the group index in the section on the sensing unit by the relation $\beta_1 = \partial\beta/\partial\omega = n_g/c$.
The reflections generated by the crossings inside each probe elements can be used also to measure the distribution of the attenuation coefficient along the waveguide. The amplitude of each reflection $|U_i|$ can be extracted from the temporal trace generated by the OFDR measurement. We can now reasonably assume that all the crossings placed in a PROW produce the same reflection and attenuation coefficients and hence we can extract the propagation losses comparing two couples of adjacent reflections $|U_i|$ and $|U_{i-1}|$. Amplitudes in the same couple differ only for the extra losses experienced by the light reflected farther from the input facet (e.g. red peak in figure 1(b)) induced by the first crossing (the blue peak) and longer propagation distance inside the probe element. Their ratio results

$$\frac{|U_i|}{|U_{i-1}|} = IL_c^2 e^{2\alpha L_j} \tag{2}$$

where IL_c is the insertion loss of a single crossing and α the attenuation coefficient. If the two considered couples of reflections have a different distance L_j between the reflectors than we can extract α with a simple linear interpolation (because IL_c is constant), effectively exploiting a cutt-back technique. This linear regression can be particularly critical if the involved lengths L_j are too small. On the other hand larger distances mean a degradation of the spatial resolution.

Experimental results

Temporal distribution of the reflections in a 6-cm long PROW are shown in Fig.2(a) while results of the extraction of the propagation losses and group index for both TE and TM polarized light from these data can be seen in Fig.2(b) and (c). The waveguide exploited for the characterization is the InP-based deeply-etched rib structure described in [3]. For the group index (Fig.2(a)) the behaviour is similar for both polarization, with a slight increasing of its value moving from the external area towards the centre of the wafer, in the order of $5 \cdot 10^{-3}$. A simulation of the expected waveguide group index variation as function

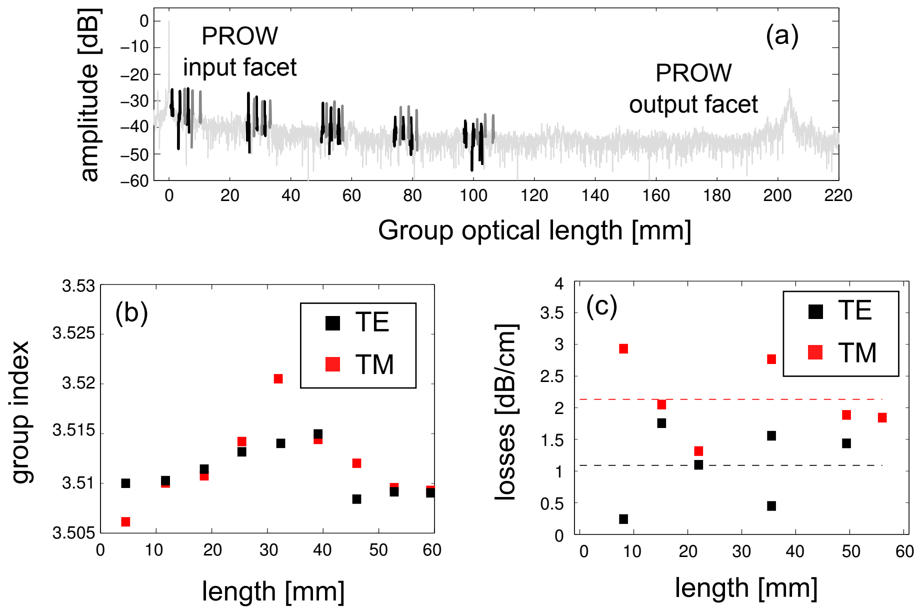


Figure 2: (a) Measured space distribution of the reflections in a PROW. Based on these data, measurements of (b) group index and (c) losses distribution are performed.

of an uncertainty in the thickness of the core layer (supposed to have the nominal value of the refractive index) reveals that this number is compatible with a variation comprised between 50 nm and 100 nm, in accordance with the specifications of the foundry.
Measurements of the propagation losses are shown in Fig.2(b). In this case a clear trend along the PROW cannot be easily recognized which suggests that the dispersion of the measured data is higher than the possible variations of α. The standard deviation of the data is about 0.5 dB for both TE and TM results, which is a good results related to the fact that the length of the involved waveguides is smaller than 0.5 cm (and hence the total insertion losses that has to be estimated are rather small and noise-affected). The average value of α for the TM mode is about 1 dB/cm higher than the TE polarized light, which is in accordance with previous measurements conducted on the same type of waveguides.

Acknowledgement

The research leading to these results has received funding from the European Community's Seventh Framework Program FP7/2007-2013 under grant agreement ICT 257210 PARADIGM.

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