Spatially Resolved Measurement of Local Attenuation and Scattering Properties of Silicon Waveguides

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Accurate determination of loss in optical waveguides is an important issue for almost every application. This characterization is typically done by cut-back measurements where the waveguide loss is determined from insertion loss measurements for several waveguide lengths. Highly reflective waveguide end facets allow for the Fabry-Pérot method where cavity resonances are examined. However, many measurements have to be done when performing the cut-back method and reflective end facets are not always available. Besides, they do not provide spatially resolved results.

Here, we show a measurement technique where the waveguide losses as well as the scattering properties of silicon waveguides can be reliably explored within one single and fast experiment [1]. Discrete defects can be located as well as linear loss within our OFDR-based method [2]. Differences in scattering due to changing waveguide widths, e.g. when using tapered waveguides, or due to the presence of top claddings can be made visible. We measure the Rayleigh backscatter from a silicon waveguide in an OFDR experiment similar to that used in [1]. The Fourier transform of the output signal yields the spatially resolved reflectivity

$$|\kappa_{\mathrm{sc}}(z)| = \exp\left(-a(z)\right) \cdot \left|\sum_n r_n h(z - z_n)\right|. \qquad (1)$$

Here, we only considered the strength of the reflected field by taking the absolute value of κ_{SC}. a accounts for the power attenuation and r_n is the complex reflection factor that characterizes the discrete scatterers at z_n. $h(z - z_n)$ denotes a spatial impulse response that mainly takes into account the limited sweep bandwidth. In our experiment, this sweep bandwidth is 40 nm and leads to a spatial resolution of around 10 μm [2]. If the mean backscatter in a waveguide does not change significantly the loss distribution can be read directly from one single measurement since the waveguide losses lead to a decrease of the light backscattered from rear positions. In general the scattering strength is not constant and the measured reflectivity contains both, loss and scattering properties. In this case they cannot be distinguished from each other within one single measurement. However, measuring the backscatter from both sides of a single waveguide enables for separating scattering from loss distribution. This is done by calculating the ratio $f_r(z)$ and the product $f_p(z)$ of the quantities given by the measurements from the left (κ^+) and right-hand side (κ^-), respectively and results in

$$f_r(z) = \frac{|\kappa^+_{\mathrm{sc}}(z)|}{|\kappa^-_{\mathrm{sc}}(\mathrm{L}-z)|} = c_1 \cdot e^{-2a(z)} \qquad (2)$$

and

$$f_p(z) = |\kappa^-_{\mathrm{sc}}(\mathrm{L}-z)| \cdot |\kappa^+_{\mathrm{sc}}(z)| = c_2 \left|\sum_n r_n h(z - z_m)\right|^2 \qquad (3)$$

where c_1 and c_2 are z-independent constants. Equations (2) and (3) show that measuring from both sides of a waveguide allows for discrimination of spatially resolved loss distribution and spatially resolved scattering properties. Performing this investigation on a 500 nm wide silicon strip waveguide of 220 nm height leads to the results shown in Fig. 1. The losses can be read from the upper curve (f_r) and are 3.8 dB/cm whereas the lower curve reveals the scattering properties of the waveguide. Fig. 2 shows loss and scattering properties of a low-loss

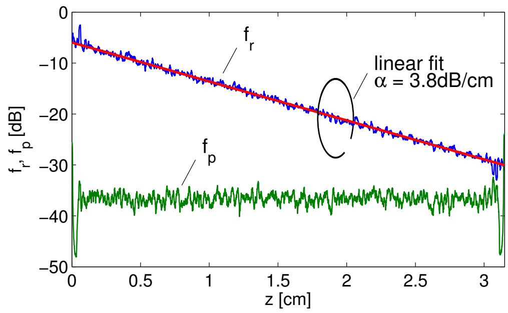

Fig. 1. Result of a two-side scattering measurement of a 3 cm long strip waveguide. The losses can be read from the upper curve (f_r), the lower curve (f_p) yields the reflectivity distribution.

($\alpha \approx 0.4$ dB/cm) silicon hybrid rib/strip waveguide [3] which is 220 nm in height and 700 nm in width in the rib sections. The slab height is 150 nm. Where turning into bends the waveguides are converted to strip waveguides to provide small and low-loss bend radii. These sections with significantly higher scattering can be clearly identified from the f_p-curve in Fig. 2. The corresponding losses per bend are below 0.01 dB and thus can not be resolved within our experiment. In conclusion, we presented an OFDR-based measurement technique for the spatially resolved determination of loss and scattering properties of silicon waveguides. Our method does not require knowledge about coupling efficiencies or any assumptions on the distribution of scatterers.

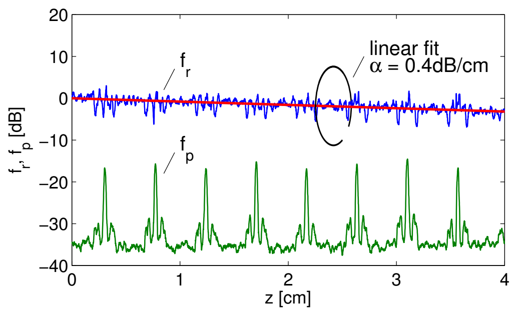

Fig. 2. Evaluation result for a low-loss nanorib waveguide with strip waveguide sections at bends (see spikes in the f_p curve).

[1] J. Müller, M. Krause, and E. Brinkmeyer, "Spatially resolved loss measurement in silicon waveguides using optical frequency-domain reflectometry," *Electron. Lett.*, vol. 47, no. 11, pp. 668–670, 2011

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[3] W. Boegaerts, and S. K. Selvaraja, "Compact Single-Mode Silicon Hybrid Rib/Strip Waveguide With Adiabatic Bends." *IEEE Photonics Journal.*, vol. 3, no. 3, pp. 422–432, 2011