The relevance of group delay for refractometric sensing

Hugo J.W.M. Hoekstra,[1,]* and Manfred Hammer[1,2]
[1]Institute for Nanotechnology, University of Twente, Enschede, The Netherlands
[2]University of Paderborn, Theoretical Electrical Engineering, Paderborn, Germany
*H.J.W.M.Hoekstra@utwente.nl

It is argued that the sensitivity of an optical sensing device, defined as the relative change of the transmittance for refractive index changes, is closely related to the group delay. Further, a general expression relating group delay and the ratio of the time-averaged optical energy and the input power is presented.

Introduction

The big potential of integrated optical refractometric sensing devices is evidenced by the large number of publications in the field, showing many different device implementations owing to the large variety of application conditions, and also to the chase after devices with a high sensitivity. The aim of this paper is to consider the relevance of the different definitions used in literature for device sensitivity and also to discuss which physical quantities are relevant for a high sensitivity.

Theory

We consider an abstract device. Assuming that the dominant noise is proportional to the transmittance, as a consequence of, for example, power fluctuations of the source, variations in detector responsivity, or mechanical instabilities, we define the sensitivity S for changes of the index n_l by

$$S = |\partial \ln T_m / \partial n_l|, \tag{1}$$

where T_m is the transmittance from the input channel to the output channel labeled m. During the conference the relevance of this definition will be compared with that of other definitions.

In our search to understand which quantities are the most relevant for high S we have considered group delay. It can be shown that for an arbitrary, non-absorbing photonic structure with given input channel with input power P_{in} the following relation holds

$$\sum_{m=1}^{Q} T_m \tau_{g,m}^{l} = \frac{1}{2}\frac{\partial(n_l\omega)}{\partial\omega}\int_{V_l} \varepsilon_0 n_l |\boldsymbol{E}|^2 \, d\tau / P_{in} \tag{2}$$

where the summation runs over the Q output channels (m), the subscript l refers to a certain material of the structure corresponding to volume V_l, ω is the angular frequency and $\boldsymbol{E}$ is the electric field. The quantity $\tau_{g,m}^{l}$ is the partial group delay for channel m, being that part of the group delay originating from the material l, which relates to the total group delay (from all P materials) via

$$\tau_{g,m} = \sum_{l=1}^{P} \tau_{g,m}^{l} \equiv -\mathrm{Im}\left(\partial \ln t_m / \partial\omega\right). \tag{3}$$

As a byproduct of the theory we present a general relation, which holds if the output modes of the structure are not overlapping with each other or with the input field, as follows

$$\sum_{m=1}^{Q} T_m \tau_{g,m} = \int_V D\, d\tau \Big/ P_{in},$$

where D is the energy density and V the volume of the considered structure. During the presentation at the conference it will be argued that partial group delay and sensitivity can be converted into each other using a simple Mach-Zehnder like interferometric set-up.

Conclusions

As to be elaborated during the workshop, a large *energy density* in the probed material relative to the input power enables the construction of a highly sensitive device. Further, a large *partial group delay*, originating from the 'sensing' part of the structure, is sufficient to construct a device with large sensitivity.