A Mach-Zehnder Interferometer with a Porous-Film Waveguide

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ABSTRACT: Porous film applied to optical waveguide allows for propagation of a peaked mode that is highly sensitive to the surrounding medium. Dependence of the effective refractive index and the profile of the guided mode on medium refractive index cause phase and amplitude modulation of fringes when this sensor is used in a Mach-Zehnder interferometer. The consequence is that a particular sensor can sense certain fluid indices better than the others. Here we present a comprehensive numerical study of such a sensor and determine the film thickness needed for sensing of different fluids: water, alcohols and oil. Fisher information is used for sensitivity determination and its applicability for characterization of classical optical sensors is confirmed.

INTRODUCTION

Multilayer optical waveguides have been widely used as evanescent-field sensors of fluid refractive index [1]. While they are small and robust, only a small portion of the propagating mode is available for interaction with the measurand, which results in poor sensitivity. In order to increase the sensitivity we suggest widening of the effective interaction area by coating a waveguide with a porous thin film. As porosity enables entering of the fluid in thin-film area, fluid interaction area expands outside the evanescent field region.

The goal of the research presented here is to provide a comprehensive theoretical analysis of a planar porous-film sensor, its application in Mach-Zehnder interferometer (MZI) and of the modulation of interferometer fringes due to the film thickness.

WAVEGUIDE WITH A POROUS THIN FILM

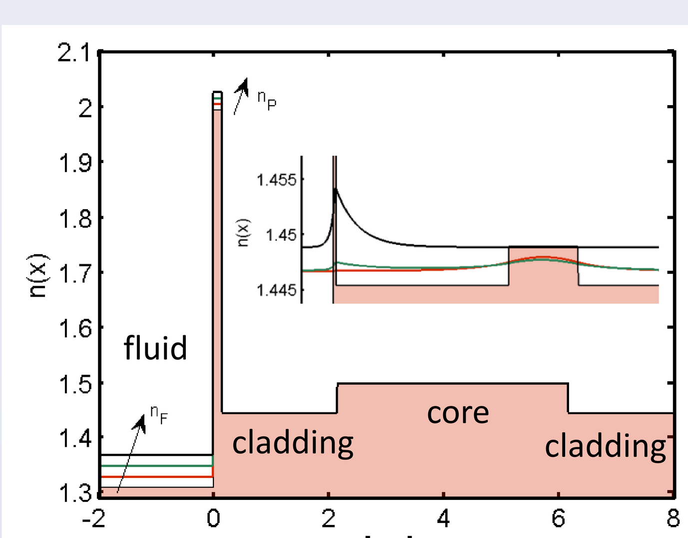

Figure.1 Refractive index profile of the sensor together with influence of fluid refractive index on the mode profile.

We have analyzed a five-layer waveguiding structure with a porous thin film on the top, interfacing fluid, Fig. 1. Correlation between the refractive index of fluid n_F, the mode effective refractive index (n_{eff}) and profile (H_y) enables usage of presented structure for sensing of fluid presence and concentration.

It is important to notice the nonlinear n_{eff} dependence on n_F and the strong dependence of supported modes intensity on n_F [2].

We also note that, depending on n_F, the guide can work in single- and two-mode regimes.

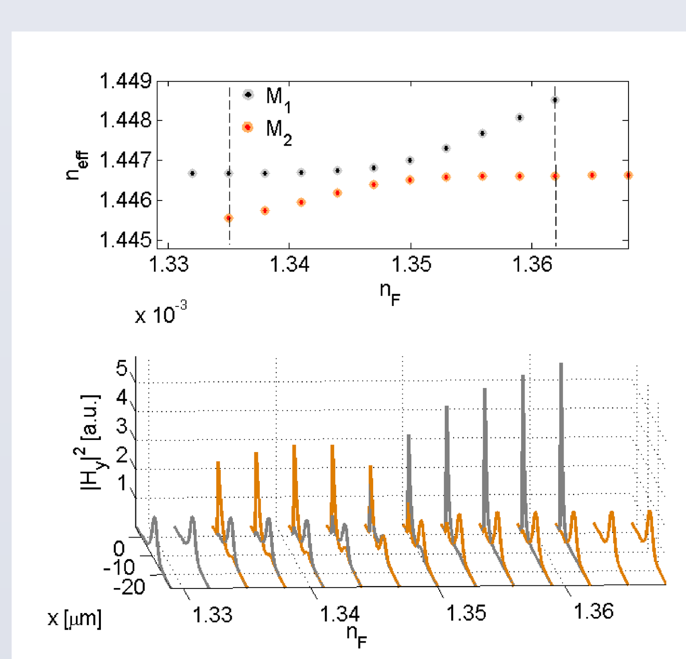

Figure.2 (a) Mode effective indices as functions of the fluid refractive index. (b) The corresponding mode field intensities. The film thickness was d_P=140nm and porosity P=32%.

MACH-ZHENDER INTERFEROMETER

The MZI is composed of a sensing arm with access to the measured fluid and a reference arm with a fixed external refractive index and two couplers. Here we assume that the output coupler simply superposes modes from different arms and calculate the output intensity as:

$$H_y(x|n_{eff}) = H_{ref}(x) + H_{test}(x)e^{-j\Delta\varphi} \qquad I_{MZI} = \int |H_y(x|n_{eff})|^2 dx$$

$$\Delta\varphi(n_F) = k_0 L_z\left(n_{eff}^{test}(n_F) - n_{eff}^{ref}\right)$$

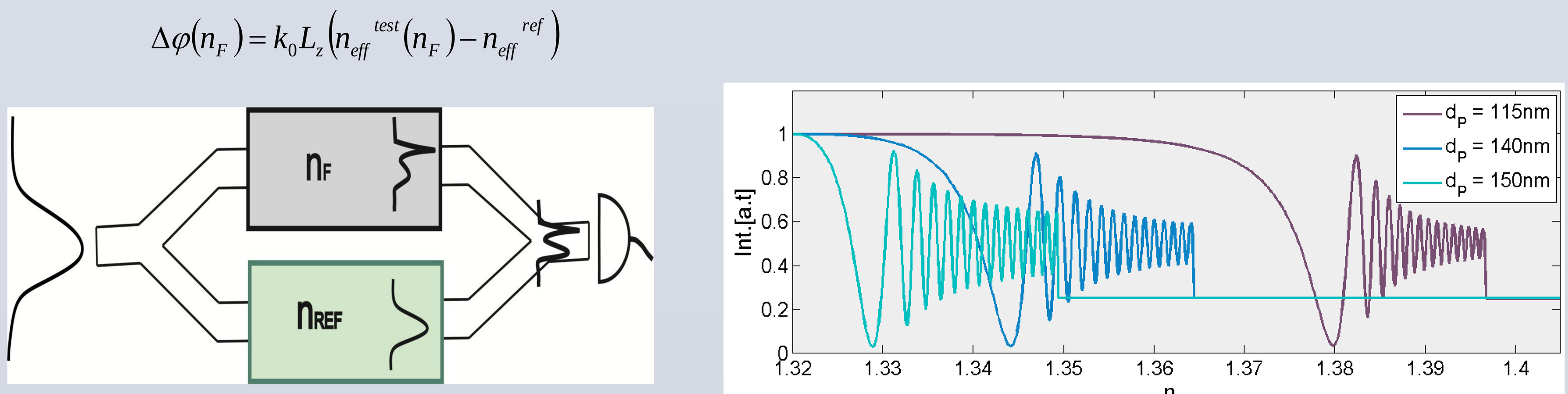

Figure 3: a) Schematic of a MZI. b) Intensity output of the MZI with a fixed porosity P = 32% and d_P as a design parameter.

The sensitivity range can be controlled by tailoring thin film thickness (Fig. 3b) as well as porosity.

SENSITIVITY

Responsivity of a MZI to the fluid refractive index change is defined as $R = dI/dn_F$. Sensitivity of a MZI is the smallest refractive index change it can sense and is defined as

$$\delta n = \Delta I / R$$

FISHER INFORMATION

Fisher information is a local probability measure and can be defined via an arbitrary **conditional probability** function with respect to a system parameter or a set of system parameters [1]. In the theory of measurement, the maximum of FI is known to limit the uncertainty of the phase estimator from below, which is known as Cramer-Rao bound. In the studied MZI, the intrinsic parameter whose measurement uncertainty is to be determined is n_F. For a typical source used in experiments (classical source with a large number of photons), the central limit theorem is valid and the conditional probability of the intensity recorded by a photodiode can be assumed to be Gaussian [3], (Fig 4).

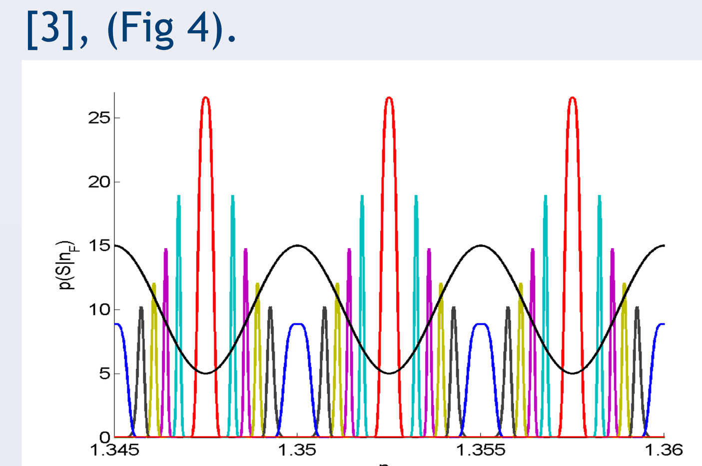

Figure 4: Probability distribution function of MZI output intensity (coloured lines). Scaled intensity output of MZI as a function of n_F (black line).

$$p(I|n_F) = \frac{1}{\sqrt{2\pi\Delta I^2}} e^{-\frac{(I-\langle I\rangle)^2}{2\Delta I^2}}$$

$$FI(n_F) = \int \frac{1}{p(I|n_F)}\left(\frac{dp(I|n_F)}{dn_F}\right)^2 dI$$

Here, <I> represents the mean output intensity, I the measured intensity, and ΔI is the standard deviation of the measured intensity that depends on the detector.

The ultimate MZI sensitivity is given by **Cramer-Rao bound**: $\delta n^{CR} = \frac{1}{\sqrt{FI_{max}}}$

Therefore, the aim of the sensor design is to maximize Fisher information.

RESULTS

Modes localized in the thin porous film are particularly sensitive to a change in the external index, Fig 2b). The dependence of their profiles and effective refractive indices on n_F causes amplitude and phase modulation of the output intensity. Figure 5 shows a typical interferometer response to a change in n_F.

Optimization across the experimentally accessible parameters d_P and P renders the highest sensitivity of $0.8\cdot10^{-6}$, which is comparable to the 10^{-5} sensitivity reported for the MZI with a porous waveguide of the same length [2]. Whereas in an unmodulated MZI the maximum sensitivity is reached for different measurand values across the whole sensing range, the modulated porous-film MZI has the maximum sensitivity at a single value of the measurand.

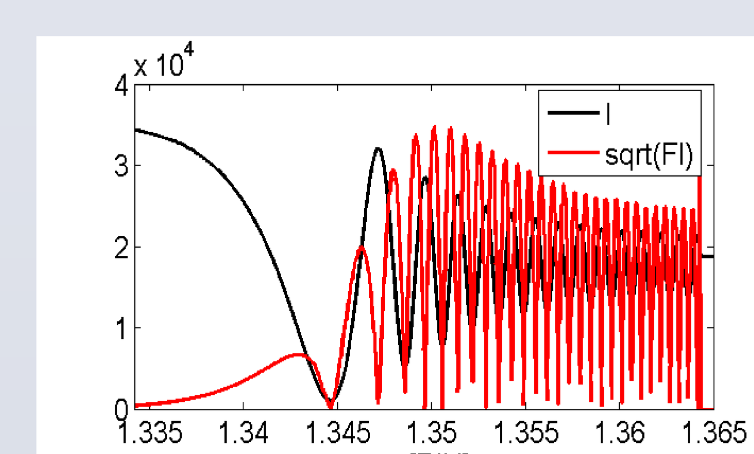

Figure 5: Interferometer output and the Fisher information calculated for the porous-film MZI.

CONCLUSIONS

MZI sensitivity enhancement by application of a porous thin film is proposed. The maximum predicted sensitivity is of the order of 10^{-5} RIU. It is higher than the sensitivity of solid-film sensors, but lower than the sensitivity of the surface plasmon-polariton sensors. Fisher information can be used for the sensor sensitivity estimation and hence as a parameter in MZI design. The proposed MZI is sensitive to sub-percent changes in the film thickness. Hence, it may be of interest as a tool for precise film characterization.

REFERENCES

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ACKNOWLEDGMENTS

The authors acknowledge support from the Ministry of Education, Science and Technological Development of Serbia (Project No. III45010).