IN-FIBER MACH-ZEHNDER INTERFEROMETER BASED ON A PAIR OF LONG-PERIOD GRATINGS

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ABSTRACT

A new type of in-fiber Mach-Zehnder interferometer based on a pair of long-period gratings is proposed. This interferometer can be used to measure the refractive index induced in fibers and that of the surrounding medium.

INTRODUCTION

The fiber Mach-Zehnder interferometer based on two 3 dB WDMs is successfully used to solve many physical tasks, for example, measuring the induced refractive index in the fiber core [1]. Phase delay in one of the interferometer's arms leads to a corresponding change in the interference signal at the fiber output. Such an interferometer is very sensitive, but has significant drawbacks. Because the fiber arms are rather long, the operating temperature must be well stabilized. As a rule a laser with a high coherence length must be used as the light source, or the interferometer arms' lengths must be equalized with high precision.

We propose a new type of Mach-Zehnder interferometer based on two 3 dB long-period gratings. This interferometer does not feature the above mentioned disadvantages and can be used for many practical purposes.

THEORY

A schematic of the interferometer is plotted in fig.1. The grating 1 directs half of the fundamental mode's power into a cladding mode. Thus a part of light power covers the distance between the gratings 1 and 2 in the fundamental mode (core arm of the interferometer) and the other part in the cladding mode (cladding arm). These two waves interact in the second grating Gr2 in accordance with the phase difference between the interferometer arms. As a result the transmission spectrum of the interferometer depends on the phase difference gained by the waves in the region between the gratings.

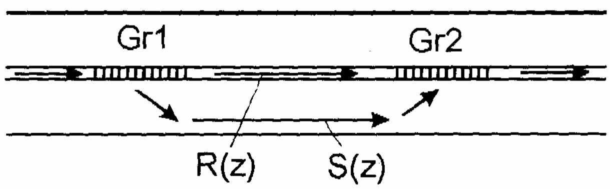

Fig.1. Mach-Zehnder interferometer scheme.

The coupled modes theory which describes the interaction of the core R(z) and the cladding S(z) modes in a single long-period grating gives the following differential equations [2]:

$$\frac{dR}{dz} + i\delta R = i\eta S$$
$$\frac{dS}{dz} - i\delta S = i\eta R \qquad (1)$$

where η is the mode coupling coefficient, proportional to the induced refractive index in the fiber core and to the overlap integral of the core and cladding modes' fields,

$\delta \approx \frac{2\pi}{\Lambda}\frac{\Delta\lambda}{\lambda}$ is the frequency deviation from the resonance (λ - the resonance wavelength, Λ - the grating period). Assuming boundary conditions $R(0) = R_0$, $S(0) = S_0$, we have:

$$\begin{bmatrix} R(z) \\ S(z) \end{bmatrix} = \hat{U}(z) \cdot \begin{bmatrix} R_0 \\ S_0 \end{bmatrix} \tag{2}$$

where

$$\hat{U}(z) = \begin{bmatrix} \cos(z \cdot \sqrt{\eta^2 + \delta^2}) - \frac{i\delta}{\sqrt{\eta^2 + \delta^2}} \sin(z \cdot \sqrt{\eta^2 + \delta^2}) & \frac{i\eta}{\sqrt{\eta^2 + \delta^2}} \sin(z \cdot \sqrt{\eta^2 + \delta^2}) \\ \frac{i\eta}{\sqrt{\eta^2 + \delta^2}} \sin(z \cdot \sqrt{\eta^2 + \delta^2}) & \cos(z \cdot \sqrt{\eta^2 + \delta^2}) + \frac{i\delta}{\sqrt{\eta^2 + \delta^2}} \sin(z \cdot \sqrt{\eta^2 + \delta^2}) \end{bmatrix}$$

In the case of interferometer described above (fig.1) we have:

$$\begin{bmatrix} R \\ S \end{bmatrix} = \hat{U}(L) \cdot \begin{bmatrix} \exp(i\Delta\varphi) & 0 \\ 0 & 1 \end{bmatrix} \cdot \hat{U}(L) \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{3}$$

where $\Delta\varphi$ is the phase difference between the interferometer arms. For simplicity, here we assume that the both gratings have equal parameters L and η, but this description can be easily generalized to the case of different gratings. The transmission spectrum of the interferometer can be expressed as $R \cdot R^*$. Fig.2 represents calculated transmission spectra of an interferometer consisting of two 1.5 cm long gratings with $\eta L = \pi/4$ for several phase differences $\Delta\varphi$. At the exact resonance (δ=0) from (3) we have at the interferometer output:

$$R \cdot R^* = 1 - \frac{\sin^2(2\eta L)}{2}[1 + \cos(\Delta\varphi)] \tag{4}$$

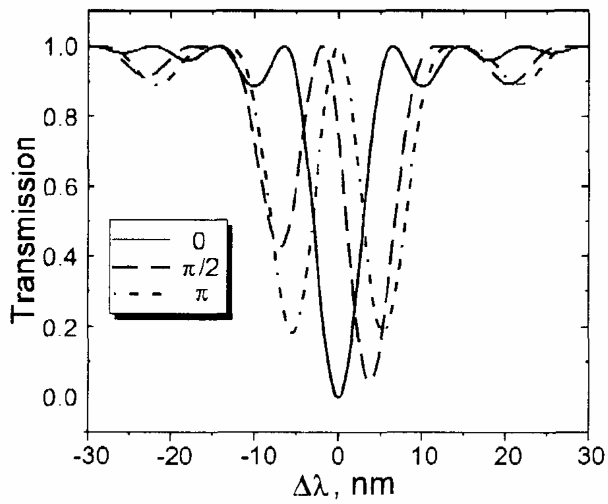

Fig.2. Calculated spectra of the interferometer.

EXPERIMENT

To prepare 3 dB long-period gratings we used a step-index germanosilicate fiber with 12 mol.% GeO_2 in the fiber core and with a cut-off wavelength of 900 nm. The gratings were written by the step-by-step technique with the aid of a CW frequency doubled Ar^+-laser radiation (λ=244 nm). The gratings had the following parameters: Λ=250 µm, L=1.5 cm. The space interval between the gratings was 1 cm.

To demonstrate operation of the interferometer we have irradiated the fiber in the region between the gratings by 244 nm UV-light with a power density of 100 W/cm². During this irradiation an additional refractive index in the fiber core was induced. As the result the transmission spectrum of the interferometer was changed. As a rough approximation one can assume that the UV-induced refractive index does not change the propagation constant of the cladding mode and therefore in this case we induce an additional phase only in the core arm. The transmission spectra at several time points during the UV-irradiation are plotted in fig.3. The curves correspond approximately to $\Delta\varphi$ of 0, $\pi/4$ and $\pi/2$. The contrast value of the interferometer was about 0.7. Fig.4 presents the time dependence of the transmission at the center of the interferometer spectrum during this irradiation. One can see that the transmission behavior corresponds to the function given by equation (4). The number of the oscillations observed allows one to calculate the UV-induced refractive index change in the fiber core. It amounted to $8.5\cdot10^{-4}$ after 80 min irradiation.

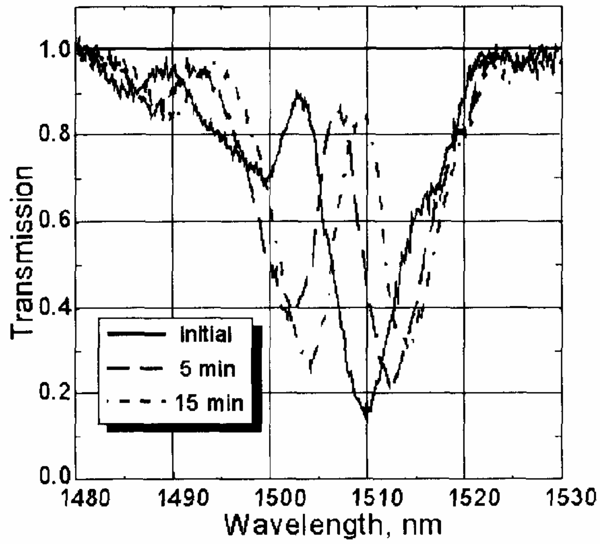

Fig.3. Transmission spectra of the interferometer during UV-irradiation.

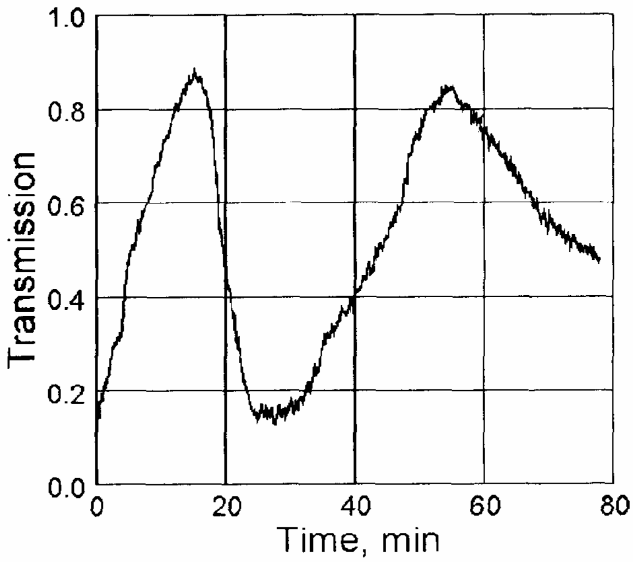

Fig.4. Time dependence of the transmission at the central wavelength during UV-irradiation.

As it was shown in [3] it is possible to increase the propagation constant of the cladding mode of the fiber without affecting the fundamental mode. For this purpose the fiber in which the grating was written can be immersed in an additional liquid with a refractive index close to that of the cladding. We immersed the sensitive part of the interferometer (L = 1 cm) in liquids with different refractive indices. The results of this experiment are plotted in Fig.5.

As is shown in fig.5a, in this case (in contrast to fig.3) the interference pattern moves towards shorter wavelengths, which corresponds to a negative phase difference $\Delta\varphi$ in (3). It should be noted that when the surrounding medium index is higher than the cladding index, the interference pattern disappears (fig.5b).

Discussions

As compared to traditional interferometers, our interferometer has the following advantages:

- small sensitivity to temperature deviations;
- possibility to use a low-coherent source;
- the ease of fabrication and operation.

It is well known that long-period gratings can be used in many important applications [4]. Obviously, the interferometer proposed allows one to correct the transmission spectrum of the grating.

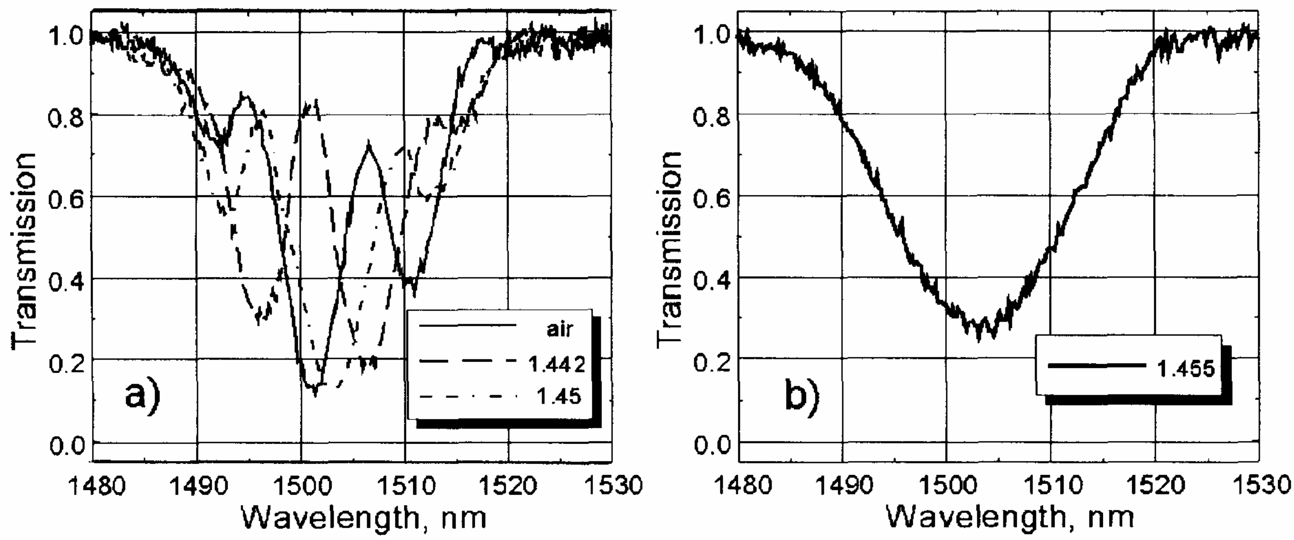

Fig.5. Transmission spectra of the interferometer with the immersed sensitive part. The refractive index of external liquid is smaller (a) and higher (b) than the cladding index.

The experiments described above show that the interferometer can be used for the measuring:

- the induced refractive index in the fiber (the estimated accuracy is better than 10^{-5});
- the refractive index of the external medium with an accuracy of 10^{-3} in the region of 1.4÷1.45;
- the presence of a liquid on the surface of a sensitive part of interferometer when liquid index is higher than cladding index.

In contrast to ordinary long-period gratings [3, 5], the interferometer allows one to carry out such measurements at one wavelength without invoking a wide transmission spectrum.

Conclusions

We have suggested a new type of in-fiber Mach-Zehnder interferometer based on a pair of 3dB long-period cladding-mode-coupled gratings. The possibility to use it as a tool for measuring UV-induced refractive index in the fiber core and the refractive index of external medium has been demonstrated. Note also that two properly adjusted gratings can be used to obtain special transmission spectra.

References

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