DISTANCE MEASUREMENTS USING OPTICAL FIBER SENSORS

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Abstract: Optical fiber sensors are widely used as displacement and distance probes. The intensity and phase modulation of the light beam is used in this technique to measure small distance changes. Several types of the fiber optic reflection and interferometric sensors were developed for those purposes. The fiber optic reflection sensors are simple in construction and are capable to measure the distances in submicrometer range. In this contribution the fiber optic reflection sensors and interferometer are described.

Meritev razdalje z uporabo senzorjev z optičnimi vlakni

Ključne besede: merjenje razdalje, ločljivost < 1μm, senzorji z vlakni optičnimi. senzorji premikov, sprememba razdalje, modulacija intenzivnostna, modulacija fazna, žarki svetlobni, senzorji optični, senzorji refleksije z vlakni optičnimi, senzorji interferometrični, PMMA polimetil metakrilat, vlakna optična večrodovna, vlakna optična enorodovna, Mach-Zehnder interferometri, Michelson interferometri, Fabry-Perot interferometri

Povzetek: Senzorji z optičnimi vlakni se v merilni tehniki uveljavljajo tudi na področju merjenja pomikov in določanja položaja. Pri meritvah majhnih pomikov s pomočjo svetlobe se uporabljajo predvsem intenzitetno in fazno modulirani senzorji. V ta namen je bilo razvitih več senzorjev z optičnimi vlakni na podlagi odboja svetlobe in interference. Odbojnostni senzor z optičnimi vlakni, ki je namenjen določanju razdalj, lahko meri pomike v območju pod mikrometrom. Z interferometrom, sestavljenim iz optičnih vlaken, pa lahko merimo še manjše pomike. V tem članku so prikazani odbojnostni in interferometrski senzorji z optičnimi vlakni za merjenje majhnih pomikov.

1. INTRODUCTION

In recent years, several fiber optic displacement sensor schemes have been suggested /1/. Most fiber optic displacement sensors are based on intensity or phase modulation of light. Those sensors can be used in many other applications as the surface finish sensor /2/, the pressure sensor /3/, and others. We developed the fiber optic refractive index sensor /4/, the fiber optic microphone /5/, and the surface pattern sensor /6/, on the base of the reflective fiber optic displacement sensors. We also developed the vibration and refractive index sensor /7/, which base on the interferometric displacement sensor.

In this paper some of the fiber optic displacement sensors are described. Basic characteristics and principles of operation are shown. This type of sensors has advantages in noncontact and remote measurements, with high resolution. They can be applied inside electromagnetic fields and explosive environments where other sensors are not usable. The optical fiber reflection sensors are simple in construction and are not sensitive to external influences if compensation technique is used /8/. On the other hand the fiber optic interferometers enable high accuracy in measuring the distances, smaller than the light wavelength.

2. INTENSITY MODULATED FIBER OPTIC DISTANCE SENSORS

Several types of the fiber optic intensity based displacement sensors have been developed. Two different configurations are possible with this sensors. In the first configuration, the light beam from LED or LD is launched into the input fiber. The input fiber delivers light through the Y coupler to the sensor tip. The light is coupled out of the fiber and reflected at the moving mirror. Part of the reflected light is captured by the same fiber and returned to the Y coupler. One part of the light travels back to the light source and the second part to the detector. The described sensor is shown on Fig. 1a.

The second configuration includes two fibers, where the first is the input fiber and delivers the light to the mirror. The reflected light is captured by the output fiber and the receiving diode. This configuration is presented on Fig. 1b. The sensor performance can be enhanced by ano-

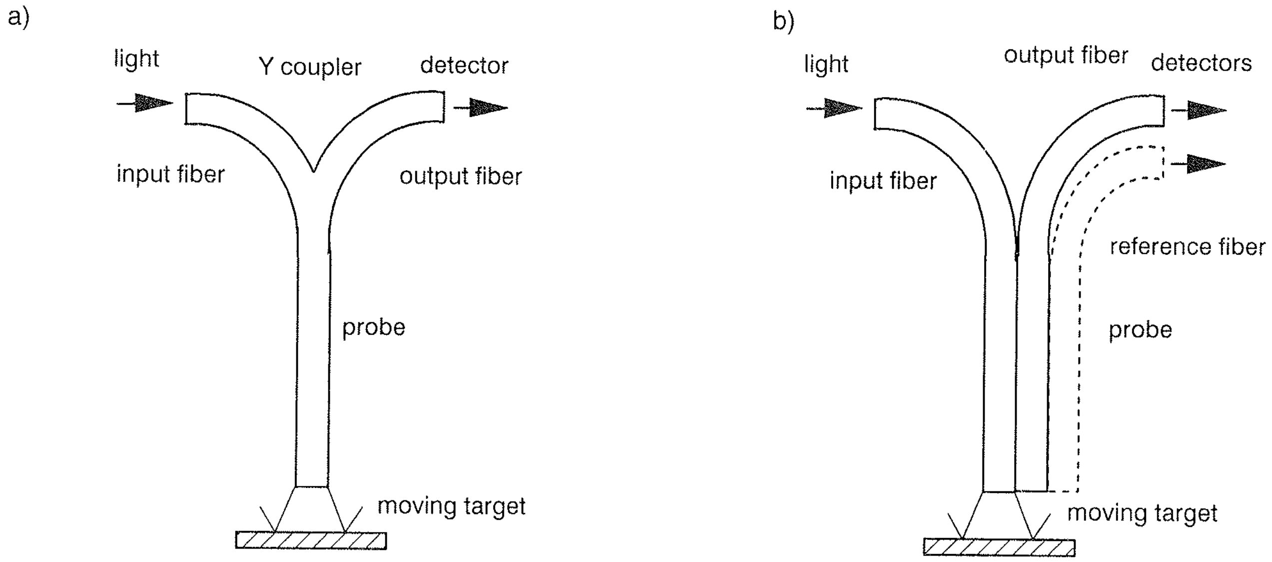

Fig. 1: Reflective fiber optic sensors including a) Y coupler and b) two fibers.

ther output fiber which is added parallel to previous one (dashed lines in Fig. 2b). The output fibers guide the light to separate receivers. By measuring the ratio of both outputs, the light source intensity variations, reflectivity of the mirror, opacity of the transmitting medium as well as light bending losses can be eliminated /8/. The bending losses can be neglected if both output fibers are in close contact and have equal curvature radius.

Different types of optical fibers were used. The standard monomode and multimode telecommunication silica fibers, and multimode fibers made of polymethyl methacrylate (PMMA) were used. The core diameter was 9 μm for the monomode silica fiber, 50 μm for the multimode silica fiber and 1 mm in case of PMMA fiber. The output characteristics for monomode and multimode silica fibers are shown on Fig. 2a. Both sensors employ Y coupler. The monomode optical fiber probe has better sensitivity than the multimode and enables the measurement of the displacement with resolution below 1 μm and dynamic range of 50 μm. The multimode probe has wider dynamic range (100 μm).

The multimode PMMA fibers were used in a two fiber probe. The sensor characteristic is shown on the Fig. 2b and is linear before reaching the maximum. The signal from the second output fiber was measured also. The compensated signal is derived by dividing both output signals. The compensated sensor has good time stability and wider dynamic range.

The theoretical descriptions and additional comments on the multimode fiber optic reflection probe consisting of Y coupler and two fibers were explained in Ref. 6 and Ref. 4.

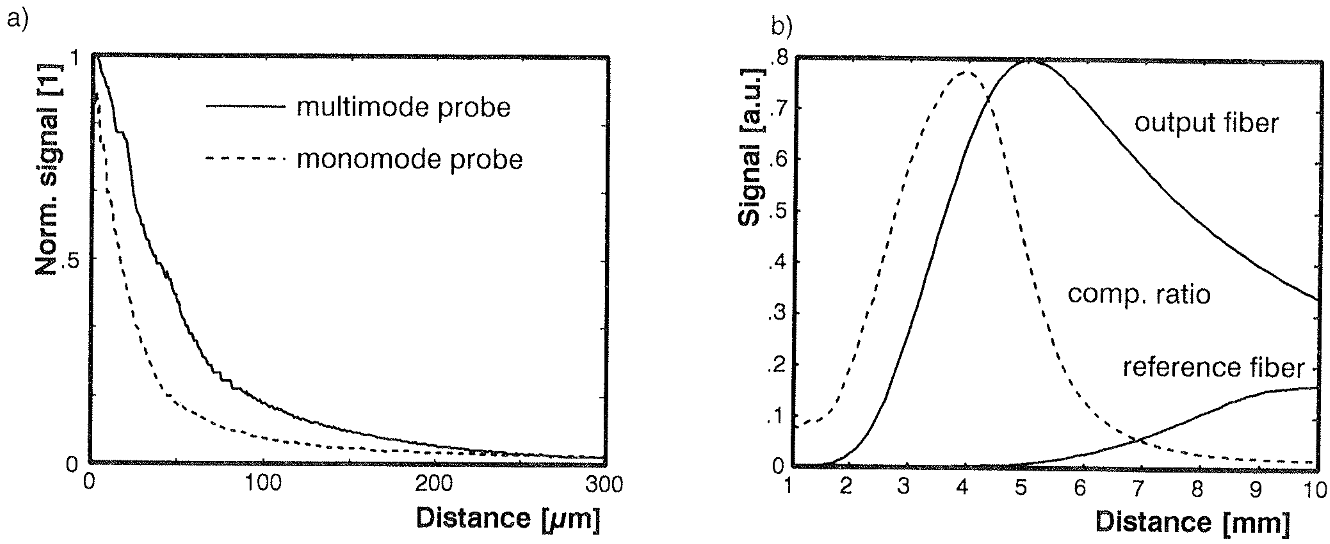

Fig. 2: Sensor characteristic for a) monomode and multimode silica probes and b) multimode PMMA probe with double output and compensated signals.

3. PHASE MODULATED FIBER OPTIC DISTANCE SENSOR

The fiber optic interferometers allow measurements of differential phase shifts in the optical fiber generated by the external physical or chemical parameters. The optical phase change ϕ in the interferometer is equal /8/

$$\phi = nkL, \tag{1}$$

where n is refractive index of the medium, k is the optical wavenumber defined by the light wavelength λ as $k=2\pi/\lambda$, and L is the path length of the light. If the phase variations are small the equation 1 must be differentiated and the phase change $d\phi$ can be expressed by the changes of n, k, or L

$$d\phi/\phi=dn/n+dk/k+dL/L. \tag{2}$$

Three basic fiber optic interferometer configurations which used for the distance measurements are Michelson, Mach-Zehnder and Fabry-Perot interferometer. The Mach-Zehnder configuration is shown in Fig. 3.

In the Michelson and Mach-Zehnder interferometers the signal and the reference arm are separated, while in Fabry-Perot configuration the signal and reference light beam travels through the same fiber. In experiments the hybrid Mach-Zehnder configuration was used (Fig. 4a). Monomode fibers and X coupler were incorporated in this arrangement.

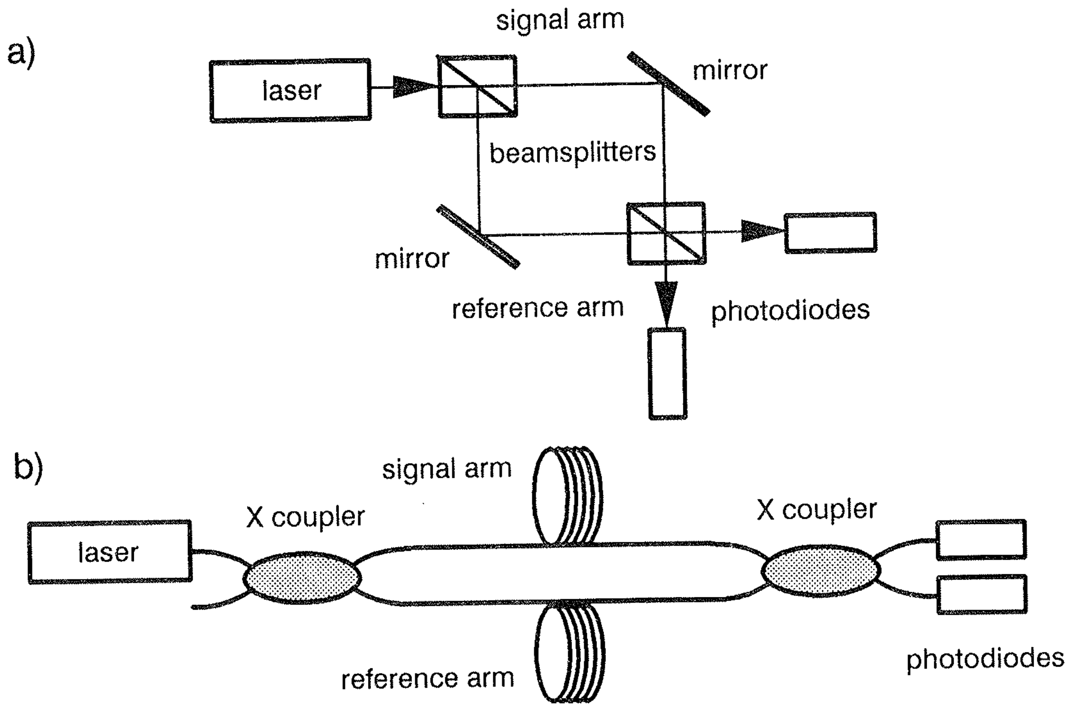

Fig. 3: Mach-Zehnder interferometer a) conventional b) fiber optic

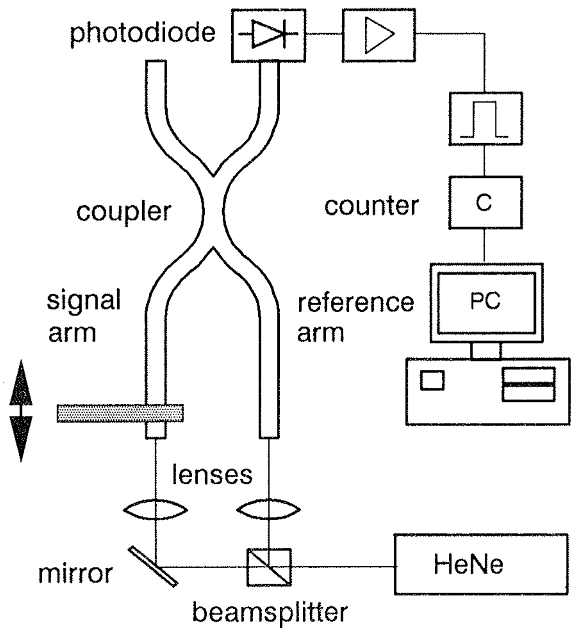

Fig. 4a: Experimental interferometer

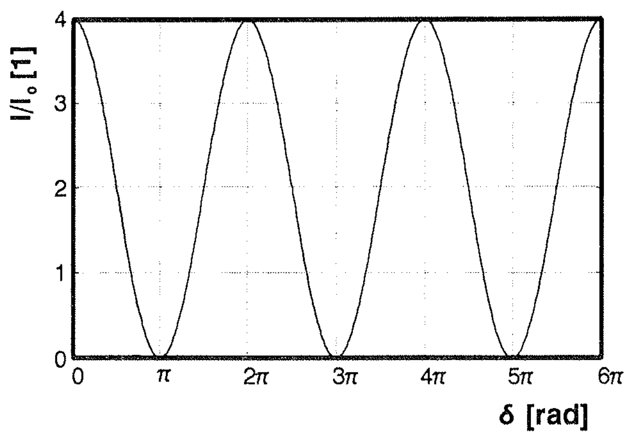

Fig. 4b: Interferometer signal

In the hybrid Mach-Zehnder interferometer only the second beamsplitter is the fiber optic X coupler. The proposed configuration enables distance measurements in wide range. The distance range is limited only by the coherence length of the light source. In this configuration a HeNe laser (λ=633 nm) was used with coherence length approximately 1 cm. The signal fiber was attached to the moving stage and the phase change was achieved by moving the stage. The receiving electronics is capable to count multiples of π of the phase change. The path difference *L* can be determined from the equation 1 and is equal to $\lambda/2$ for one count. The output intensity on photodiode *I* can be determined from the following equation

$$I = Is + Ir + 2\sqrt{I_s\, I_r}\cos\delta \qquad (3)$$

where I_s is intensity in the signal fiber, I_r the intensity in the reference arm and δ is the phase difference between both arms. In Fig. 4b the ideal interferometer response is shown where the $I_s=I_r=I_0$ ($I=4I_0\cos^2(\delta/2)$). In real interferometer the response is between the maximum and minimum of the ideal response. The light coupling in the beamsplitter and fiber coupler is not perfect and the light losses in both arms are not equal. Small displacements can be measured with a similar interferometric setup where the compensator is added in the reference arm. The compensator shifts the phase and holds the interferometer at the point of maximal sensitivity (interferometer quadrature).

4. CONCLUSIONS

Several fiber optic displacement measurement techniques are discussed in present paper. The reflection type sensors are simple in construction and provide resolution of less than 1 μm. The dynamic range and sensitivity are determined by the geometrical arrangement of the sensor. The compensated technique increases the sensor stability.

The interferometric sensors have wider dynamic range and higher resolution but are complex in construction. The Mach-Zehnder interferometer enables resolution of $\lambda/2$ by using the fringe counting technique.

5. LITERATURE

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