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Proposed design for high precision refractive index sensor using integrated planar lightwave circuit

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Abstract

A high precision and compact refractive index sensor is proposed. The combination of coarse measurement utilizing the change of the angle of refraction and fine measurement utilizing the phase change is newly proposed to measure absolute refractive index precisely. The proposed method does not need expensive optical measurement equipment such as an optical spectrum analyzer. The integrated planar lightwave circuit (PLC) technology enables us to obtain a compact sensor that is preferable for the practical use. The principle, design, and some configurations for precise refractive index measurement are described.

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Keywords: Integrated optics; Refractive index sensor; Optical planar waveguides

1. Introduction

Refractive index sensing has received a lot of attention in application to the fields of biochemistry, chemical and environmental analysis, and others. For the practical use in these applications, compactness, low-cost, and real-time measurement should be essential as well as high resolution and precision.

For these applications, optical sensing is attractive to measure the refractive index directly and precisely. Many methods for refractive index sensing have been proposed such as the use of surface plasmon resonance (SPR) [1-3], Fabry-Perot interferometers [4], resonance in photonic crystals [5], and fiber Bragg gratings [6-8]. For typical refractive index sensors using Fabry-Perot interferometers, the phase passing through a cavity filled with the material (liquid) under test is measured. In this method, the resolution can be improved by using a longer cavity. However, it is difficult to measure the absolute value of the refractive index because the measured phase folds into a

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period of 2π rad. Sensors using optical fibers have typically less resolution compared by other methods although the refractive index can be easily measured by using the fiber itself as a sensing probe. With the methods using SPR and photonic crystals, very small amount of material can be measured. However, most of these methods need expensive optical measurement equipment such as an optical spectrum analyzer (OSA) at the outside of a sensing unit to measure the spectrum of reflected or transmitted light. The resolution and accuracy is highly dependent on the optical measurement equipment. In actual, therefore, it is difficult to measure the refractive index with high resolution (10^{-6} or less) due to the limitation on the precision of the equipment although some of these methods have potentially high precision characteristics. Moreover, most of these methods, except for the optical fiber type, uses bulk optical system. Therefore, more compact sensor should be necessary in the practical use.

In this paper, high precision and compact refractive index sensor is proposed. In the proposed structure, the combination of coarse measurement utilizing the change of the angle of refraction and fine measurement utilizing the phase change is newly used to measure absolute refractive index precisely. The proposed sensor does not need expensive optical measurement equipment such as an OSA. The integrated planar lightwave circuit (PLC) technology [9-16] enables us to obtain a compact sensor that is preferable for the practical use. The principle of the proposed method and the design using the PLC are described. Some configurations for precise refractive index measurement are also proposed.

2. Principle

Figure 1 illustrates the concept of the proposed refractive index sensor. In this method, a new concept using the combination of coarse measurement utilizing the change of the angle of refraction and fine measurement utilizing the phase change is proposed to measure absolute refract index precisely.

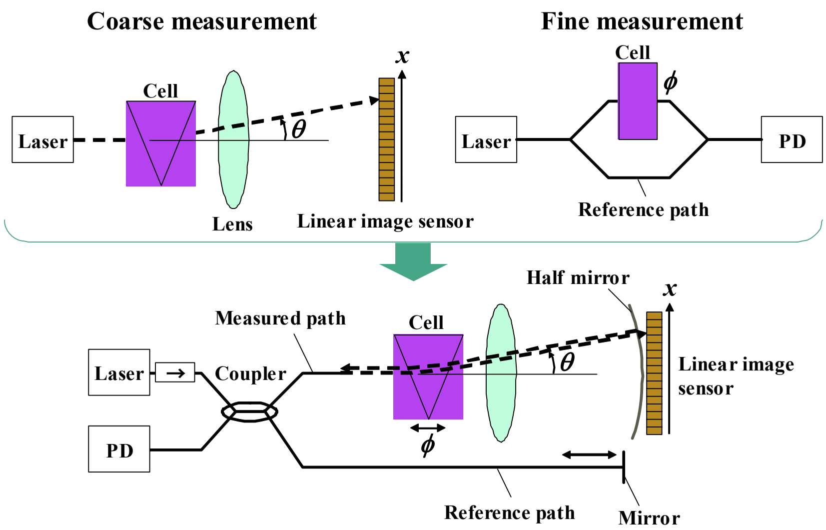

Fig. 1. Concept of proposed refractive index sensor.

The absolute value of refractive index can be measured by measuring the angle of refraction of the beam passing through a wedge-shaped cell filled with the material (liquid) to be tested. In this method, however, there is a trade-off relationship between the resolution and size, i.e. the size should be larger for higher resolution. Meanwhile, high resolution can be easily achieved by measuring the phase change of the beam passing through the material by using optical interferometry. However, the absolute value of the index is difficult to measure over wide index range. The proposed method solves these difficulties in each method.

In the proposed method, the angle of refraction and the phase are simultaneously measured by using a wedge-shaped cell and optical interferometry. A Michelson interferometer is formed with a measured arm, consisting of a wedge-shaped cell, lens, and half mirror, and reference arm. The beam from a laser is first divided with a coupler. One beam propagates a measured arm, reflects at a half mirror, and comes back through the measured arm again. Another beam propagates a reference arm consisting of a single-mode waveguide, reflects at a mirror, and comes back through the reference arm. Two beams are then coupled and detected by a photodiode (PD).

The angle of refraction is measured as the position of the focusing beam through the half mirror by using a linear image sensor in which charge-coupled devices (CCDs) or PDs are lined. Simultaneously, the phase is measured as the power of the output signal from an interferometer detected by another PD. Then, the refractive index of the material under test is calculated from the power distribution detected by the linear image sensor and the power detected by the PD using a personal computer (PC). Therefore, the expensive optical measurement equipment is not needed in the proposed method. Moreover, the method is capable for realizing real-time measurement because the data from the image sensor and the PD can be simultaneously measured and analyzed by a PC.

3. Design of optical circuit

Bulk optical system has been widely used as optical interferometers for precision measurement. However, conventional optical interferometers using bulk optical system have large sizes and complexity of assembly, and are often affected by environmental disturbances, such as vibration, due to large optical path length in the optical system. Thus, optical interferometers with high precision and small size have been highly demanded.

The PLC technology enables us to obtain a compact sensor that is preferable for the practical use. The optical path length of the interferometer can be drastically reduced by using an optical waveguide circuit, in which several optical elements are arranged on a planar surface of a silica or semiconductor substrate, instead of bulk optical system. The optical waveguide circuit can be fabricated based on PLC technology that has been widely used for optical passive devices deployed for optical communication systems.

Figure 2 illustrates an example of the refractive index sensor using the PLC. The measured arm consists of an arrayed waveguide grating (AWG), which acts as a dispersive element and lens. A trench is formed in a slab waveguide of the AWG. On measurement, the trench is filled with the material under test. Because the trench has very small volume (typically several hundreds of nano liters), the refractive index of the liquid with very small volume can be measured.

At the trench, a loss occurs due to the diffraction in vertical direction. To reduce diffraction loss, the author has proposed a trench structure in which the trench is divided and arranged with the appropriate interval for the use of athermal arrayed waveguide gratings [17,18]. The trench structure can be easily applied to the proposed sensor.

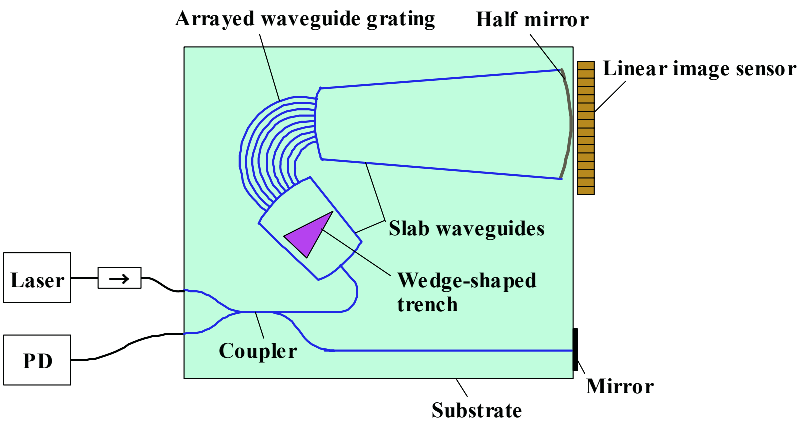

Fig. 2. Refractive index sensor using PLC.

4. Phase measurement

To improve the resolution of the refractive index measurement, the phase difference between the measured path and reference path should be precisely measured.

Figure 3 illustrates the structure using a 90^o hybrid circuit and two PDs to improve the resolution of the phase. Since the output powers of the beams from the 90^o hybrid changes sinusoidally and cosinusoidally as the phase changes, more precise measurement of the phase can be expected compared with the structure using one PD as Fig. 2. An example of the design parameters of this structure is listed in Table 1. The resolution for these parameters is estimated to be about $1x10^{-6}$ when the resolution of the phase is assumed to be 1^o. The measurement range of the refractive index is estimated to be about 1.0 to 2.0.

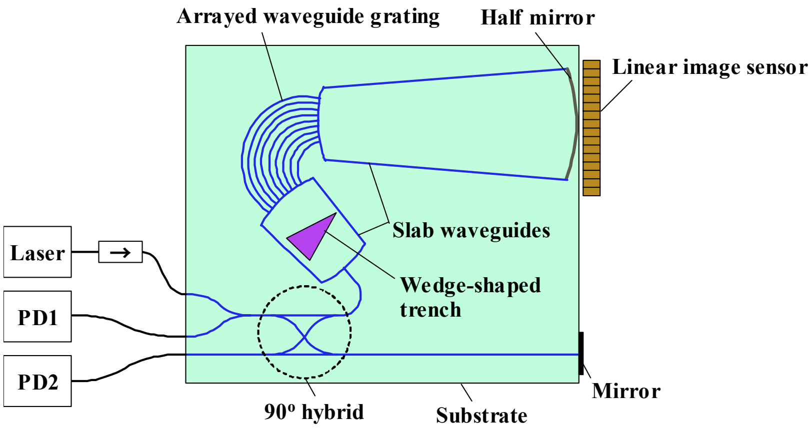

Fig. 3. Example of refractive index sensor using 90^o hybrid circuit and two PDs.

Table 1 Example of design parameters.

Focal length of output slab in AWG	50 mm
Opening angle of wedge-shaped trench	30^o
Interval of elements in linear image sensor	15 μm
Number of elements in linear image sensor	1400

As an alternative approach, using heterodyne interferometry is a promising way for precision phase measurement. Figure 4 illustrates the structure using heterodyne interferometry. A laser diode (LD) -pumped Nd:YAG laser [19] is used as a lightsource for heterodyne interferometry. As a result of the photoelastic effect in solid-state, LD-pumped Nd:YAG laser's longitudinal mode is split into two orthogonal lights when there are forces acting in the Nd:YAG crystal. The beams with different frequencies are split with a polarization beam splitter (PBS). Several types of waveguide-type PBS have been proposed [20-22], which would be available for the integration with the proposed circuit. One beam is incident on the measured arm and the other beam is incident on the reference arm. Then, the reflected beams from the arms are combined with the PBS again and the beat signal of these beams is detected by PD1. From the phase of the beat signal, the phase of the measured arm can be precisely obtained.

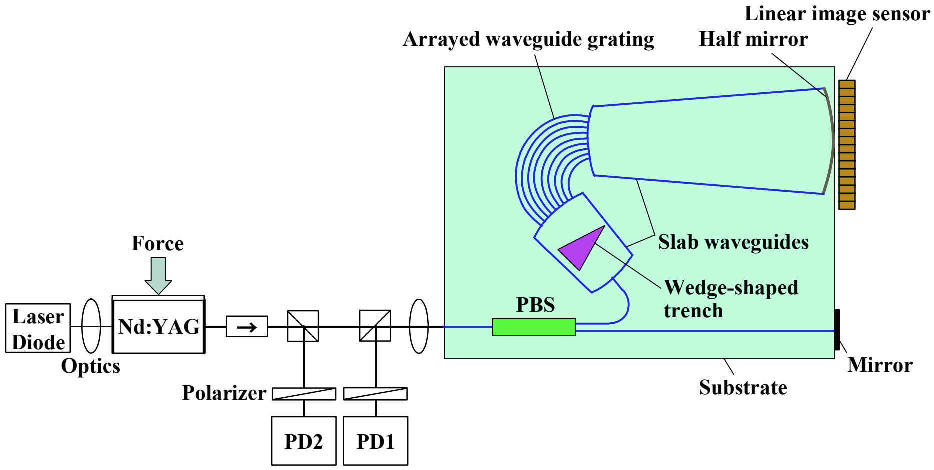

Fig. 4. Example of refractive index sensor using heterodyne interferometry.

5. Conclusion

A high precision and compact refractive index sensor is newly proposed. In the proposed structure, the combination of coarse measurement utilizing the change of the angle of refraction and fine measurement utilizing the phase change is newly used to measure absolute refractive index precisely. The proposed method does not need expensive optical measurement equipment such as an OSA. The integrated PLC technology enables us to obtain a compact sensor that is preferable for the practical use. Some configurations using the PLC are proposed for precise refractive index measurement. The proposed structure would be useful for refractive index sensing in many industrial applications.

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