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An integrated electro-optic magnetic field sensor based on reflected Mach-Zehnder interferometer

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ABSTRACT

An optical magnetic field sensor using reflective Lithium niobate ($LiNbO_3$) integrated optical waveguide Mach-Zehnder interferometer (MZI) has been proposed, designed and fabricated. The bare chip size of the sensor is microminiaturized as small as $20 \times 5 \times 0.5\,mm^3$. Experiment results reveal that the sensor has wide frequency response from 10 MHz to 2 GHz with variation less than ± 3.3 dB. Besides, the input/output of the sensor exhibit linear relationship as the magnetic field varied from 69.4 dBμA/m to 129.4 dBμA/m. The minimum detectable magnetic field is 65.4 dBμA/m and the dynamic range of the sensor is more than 60 dB.

1. Introduction

With the rapid development of electronic science and technology, electromagnetic field detection near a radiation source becomes more and more important for the electromagnetic compatibility (EMC) measurement of electronic circuit and equipment. However, the electric and magnetic fields in near-field region do not have a substantially plane wave characteristic, but vary considerably from point to point. Therefore, it is necessary to measure the electric and magnetic fields respectively for the near-field analysis. Metallic loop antenna is the fundamental tools to detect the magnetic field [1]. But, the magnetic field under measurement is disturbed by the metallic structure of the probe head, and the electromagnetic interference is picked up by the signal transmission cable during measurement. In order to solve the above difficulties, bulk optical magnetic field sensor with loop antenna element doubly loaded with $LiNbO_3$ (LN) crystal is developed [2]. As discrete optical components are required to couple the light beam into the bulk optical sensor, the measurement system becomes so complex that significantly limits its practical application in field measurements.

Integrated optical waveguide sensor has advantages of no requiring lensing system, compact size and negligible field perturbation, and has been developed for measurement of electromagnetic field [3–5]. However, as two separate optical fibers are needed to transmit the input and output optical signals respectively, the package size of the sensor is limited. Besides, the undesired electric field is induced in measurement of magnetic field by the generally single loaded sensor structure.

In this work, an integrated optical waveguide magnetic field sensor by using a reflective Mach-Zehnder interferometer (MZI) and a double loaded rectangular loop antenna is designed, fabricated, and experimentally investigated. The results demonstrate that such sensor has potential capability to be used to detect the magnetic field.

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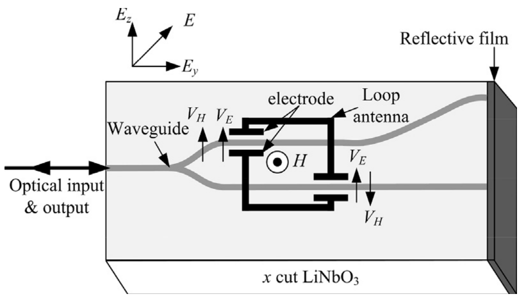

Fig. 1. Schematic configuration of the integrated optical sensor.

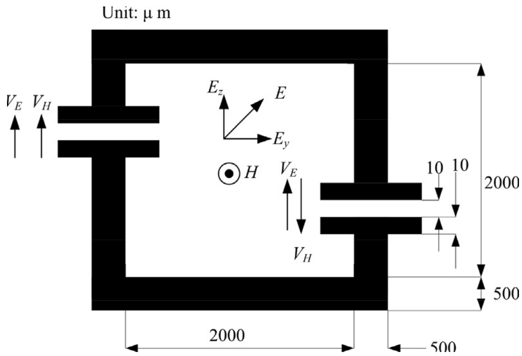

Fig. 2. Geometry structure and size parameters of the loop antenna.

2. Sensor operation principle and fabrication

The sensor configuration is shown schematically in Fig. 1. The linear polarized light beam is transmitted into the optical waveguide by polarization maintaining fiber (PMF). Consider the case that a magnetic field H penetrating perpendicularly into the loop antenna aperture where an electric field E is present on the loop plane (Fig. 1). A voltage V_E is induced across the electrode gap by E_z while the voltage induced by E_x is cancelled due to the fact that the structural of the probe is symmetry. Simultaneously, a voltage V_H is induced across the electrode gap by H base on the Faraday's law of electromagnetic induction (Fig. 2). Therefore, the total phase difference $\Delta\varphi$ of the light beam reflected back through the reflective film after travelling through the input Y branch and can be given as

$$\Delta\varphi = 2(\varphi_1\text{-}\varphi_2) = 2\pi/V_\pi[(V_E+V_H)\text{-}(V_E\text{-}V_H)] = 4\pi V_H/V_\pi, \tag{1}$$

where, V_π is the half-wave voltage of the MZI modulator. From Eq. (1), it can be seen that the modulation result is doubled using the reflective type MZI. Besides, from Eq. (1), only the magnetic field H leads to an optical modulation, which means that the undesired electric field E is eliminated using such doubly loaded loop antenna structure. The output of the sensor is given as [6]

$$P_{out} = 1/2P_{in}\alpha[1 + \cos(4\pi V_H/V_\pi + \varphi_0)], \tag{2}$$

where, P_{in} is the input optical power, α is insertion loss of the sensor, and φ_0 is the intrinsic phase difference comes from the asymmetric of the fabricated optical waveguide MZI. The asymmetric integrated optical waveguide MZI with a length difference of ΔL is designed to make it possible to control the operation point by wavelength tuning. The detailed principles of such control technique have been presented in our previous work [7]. Therefore, in Eq. (2), φ_0 is written as

$$\varphi_0 = 4\pi/\lambda n_{eff}\Delta L, \tag{3}$$

where, λ is the operation wavelength of the sensor and n_{eff} is the effective refraction index of the optical waveguide. From Eq. (3), if φ_0 is controlled equal to $\pi/2$ by wavelength tuning, then under the condition of $V_H \ll V_\pi$, Eq. (2) is simplified as

$$P_{out} = 1/2P_{in}\alpha[1 + \cos(4\pi V_H/V_\pi + \pi/2)] \approx 1/2P_{in}\alpha[1\text{–}4\pi V_H/V_\pi]. \tag{4}$$

Consequently, the output of the optical sensor is linear with the magnetic field induced voltage V_H. As a result, according to Eq. (4), the magnetic field H can be extracted using a photodiode (PD) for photoelectric conversion.

The sensor is fabricated on x-cut y-propagating LN substrate. The waveguide is fabricated by proton exchanging in benzoic acid with small amount of lithium and benzoate. Because the annealed proton-exchange process result in the extraordinary index is noticeably increased while the ordinary index is unnoticeably decreased, only the TE polarization mode is supported