A Heterodyne Optical Fiber Current Sensor Based on a Nanowire-Grid In-Line Polarizer

Yun Zhao, Feng Zhou, Fei Xu, and Yan-Qing Lu, *Senior Member, IEEE*

National Laboratory of Solid State Microstructures and College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, China

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Abstract: A heterodyne optical fiber current sensor based on a nanowire-grid (NWG) in-line polarizer is proposed. The NWG is a one-dimension Au grating fabricated on a fiber tip by focused ion beam machining. Because the grating pitch is far smaller than the wavelength of the incident light, it works like an in-line transflective fiber polarizer with both the transmission and reflection light power being measured simultaneously. Based on this unique feature, an all-fiber optical current sensor is demonstrated. The heterodyne measurement makes it withstand light power variations showing good sensing stability. As an all-fiber sensor, discrete and bulky optical components are saved, making it more reliable in practical applications.

Index Terms: Fiber optics systems, sensors, subwavelength structures.

1. Introduction

The optical fiber current sensors have been intensively studied in the past three decades [1], [2]. Compared with conventional current sensing techniques, which employ Hall effect or oil-filled transformers, optical fiber current sensors have a number of inherent advantages, such as lightweight, compact size, immunity to electromagnetic interference, and being compatible with modern fiber-optic network. Since the first optical fiber current sensor was demonstrated by Smith [3], various current sensors have been proposed that may be divided into two major kinds: the first kind is based on fiber Bragg grating that utilizes the current-induced heating or magnetostrictive effect to detect the current change [4], [5]. Although they vary from type to type, these current sensors rely on mechanical movement that may be vulnerable to environmental impact and with relatively slow response. The second kind of optical fiber current sensors is based on Faraday effect [6]–[10], which detects the state of light polarization rotated and the phase shift in the magnetic field generated by current flow. They can be very accurate and with fast response time. However, as the effective Verdet constant of optical fiber, which is consisted mostly of silica, is very small [11], the Faraday effect is not very obviously observed. As a result, there was work including hybrid system of fiber- and bulk-optic components that exploit materials such as Bi-substituted iron garnet (BIG) with a much larger effective Verdet constant compared with optical fiber [12], [13]. Other attempts include increasing the Verdet constant of fibers using high concentrations of transitions metals [14], [15]. To improve the sensing ability, a Wollaston prism is employed to build heterodyne measuring system at the signal detection end [16]–[20]. In both of the methods above, some bulk-optic components are used, which may introduce the instability to optical system and

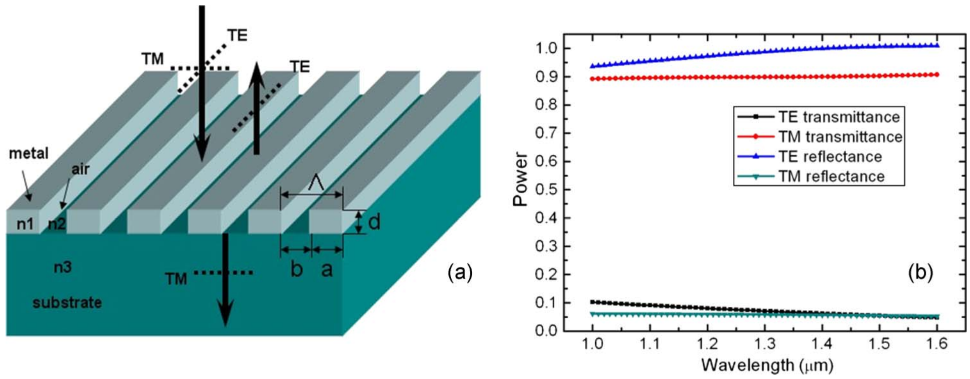

Fig. 1. (a) The work principle of an NWG. (b) The contrast of transmission and reflection light power through the NWG for TE and TM modes, respectively.

also affect the integration of optical fiber sensors, resulting in some potential reliability issues in practice applications.

In this paper, we propose an all-fiber optical current sensor without any bulk-optic component by using a nanowire-grid (NWG) fiber polarizer [21]–[23]. The NWG is actually gold wire grating fabricated on a fiber tip by focused ion beam (FIB) machining. The NWG has an interesting characteristic of reflecting TE mode part of incident light while transmitting the TM part. Both the reflected and transited light can be collected and detected simultaneously. The ratio of the two parts is determined by the state of polarization of the incident light to the NWG. As a result, the NWG can be regarded as an integrated counterpart of the Wollaston prism. Using it to build up an in-line optical heterodyne system, we demonstrate a simple all-fiber current sensor based on Faraday effect. One of its great advantages is to withstand light power variations showing good sensing stability. In the following sections, we first introduce the working principle of the NWG. Then, we give out the detailed fabrication and packaging process of an NWG on an optical fiber tip. After that, an all-fiber current sensor based on it is proposed, and heterodyne sensing experimental results are presented.

2. NWG Polarizer

A grating with its period far smaller than the light wavelength λ can be treated as an equivalent medium whose effective refractive indices can be expressed in simple forms. According to the effective medium theory (EMT), we can obtain the wave vectors of different modes propagating in the medium, i.e., TE mode (electric field parallel to grating wires) and TM mode (electric field perpendicular to grating wires), as shown in Fig. 1(a). Some recent studies have also treated the NWG as a kind of metamaterial due to its quite different TE and TM behaviors. Counting the second order of the period-to-wavelength ratio Λ/λ, Rytov solved the effective dielectric constants according to the EMT [24]

$$\begin{cases} \varepsilon_{TE} = \bar{\varepsilon}\left[1 + \frac{a^2b^2}{12\Lambda^2}\left(\frac{\omega}{c}\right)^2\left(n_1^2 - n_2^2\right)\frac{\varepsilon_1-\varepsilon_2}{\bar{\varepsilon}}\right] \\ \varepsilon_{TM} = \tilde{\varepsilon}\left[1 + \frac{a^2b^2}{12\Lambda^2}\left(\frac{\omega}{c}\right)^2\frac{\bar{\varepsilon}^2\tilde{\varepsilon}^2}{\varepsilon_1^2\varepsilon_2^2}\left(n_1^2 - n_2^2\right)\frac{\varepsilon_1-\varepsilon_2}{\bar{\varepsilon}}\right] \end{cases} \quad (1)$$

$$\bar{\varepsilon} = \frac{1}{\Lambda}(a\varepsilon_1 + b\varepsilon_2), \quad \frac{1}{\tilde{\varepsilon}} = \frac{1}{\Lambda}\left(\frac{a}{\varepsilon_1} + \frac{b}{\varepsilon_2}\right), \quad n_1 = \sqrt{\varepsilon_1\mu_0}, n_2 = \sqrt{\varepsilon_2\mu_0} \quad (2)$$

where a and b are the widths of the two kinds of material forming the grating; ε_1 and ε_2 are their dielectric constants, respectively; and μ_0 and c are the magnetic permeability and light velocity in vacuum. According to [24], the rigorous treatment agrees with those of the effect index with grating pitch smaller than 0.15λ. As a consequence, (1) and (2) should be valid if $\Lambda/\lambda < 0.15$. A smaller value may give more accurate results.

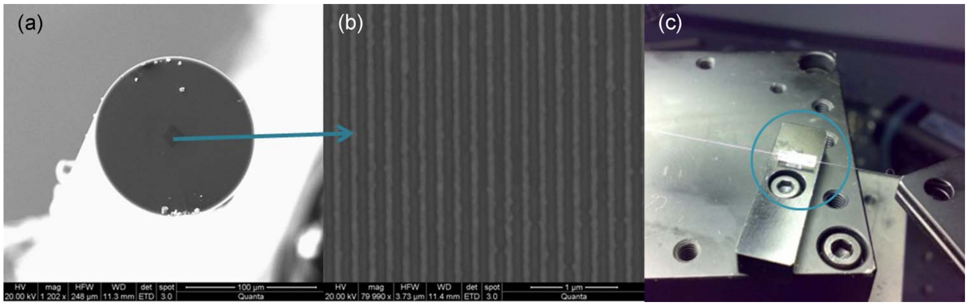

Fig. 2. (a) An SEM image of the NWG fabricated on a fiber tip. (b) Magnified image of the NWG structure in detail. (c) A glass tube packaged NWG in-line fiber polarizer.

Due to the feasibility of various light sources, many fiber-optic devices operate around 1550-nm telecom band. In this case, to make the pitch smaller than 0.15λ, a Au NWG with 200-nm period is selected. From the more rigorous multiple-beam interference theory [25], the complex coefficient of transmission t of an incident light beam normal to the grating plane can be calculated, where the substrate is the core region of a single-mode fiber (SMF), whose refractive index is $\sim$1.47. Fig. 1(b) shows the transmission and reflection power of an incident light normal to the grating plane as a function of the light wavelength. The thickness of metal is 100 nm, and the duty cycle is 0.5. These parameters are also determined according to our current equipment condition and fabrication technique, which still have not been well optimized. As illustrated in Fig. 1(b), for a TE mode, more than 95% of the light power is reflected by the NWG, while for a TM mode, nearly 90% of the light power can transmit through it. Since the transmitted light can be measured directed by a fiber power detector, and the reflected light is also detectable through an optical fiber circulator, the fiber tip NWG can principally be used as a kind of fiber-based counterpart of a Wollaston prism. From Fig. 1(b), the extinction ratio of reflected light is slightly greater than the transmitted one. To improve the performances, the NWG parameters could be further optimized.

3. Experimental Results and Discussion

We fabricate the NWG on the tip of an SMF by using FIB technology. A 3-cm segment of an SMF-28 fiber is employed. First, the polymer jacket outside the SMF is peeled off, and both end faces are cut into flat planes with fiber cleaver. Then, an 80-nm-thick layer of Au is deposited onto one end face by magnetron sputtering. After that, FIB (Strata FIB 201, FEI company, 30-keV Ga ions) is used to etch the nanowire structure on the Au coating. For saving the cost and time, we only fabricate the structure that just covers the core area of the fiber, as shown in Fig. 2(a). The machining zone is a 12 μm $\times$ 12 μm square at the center of the fiber tip. Considering the 10.4 ± 0.8 μm mode field diameter of an SMF, the grating area should be large enough. The etched time is controlled carefully to ensure a full penetration in the Au film. The period and duty cycle of the NWG are set to be 200 nm and 0.5, respectively. Fig. 2(a) shows the scanning electron microscope (SEM) images of the NWG on a fiber tip, and Fig. 2(b) shows a more detailed grating structure in greater magnification.

To realize a compact in-line fiber polarizer, we package the NWG within a tiny glass tube. The glass tube's inner diameter is 127 μm, so it can work like a simple connector for the 125-μm-diameter SMF. We put the SMF with NWG on its tip into one end of the glass tube and put another SMF without any tip structure into the other end. In the tube, two fiber tips are moved forward slowly as close as possible. After that, some epoxy is applied onto the two ends of the glass tube to fix the fibers. To avoid destroying the frangible fiber tips, all the packaging process are operated on a microscope stage.

A packaged NWG in-line fiber polarizer is shown in Fig. 2(c). We test its polarization contrast at 1550-nm wavelength. A 16.3-dB reflection contrast and a 4.8-dB transmission contrast are

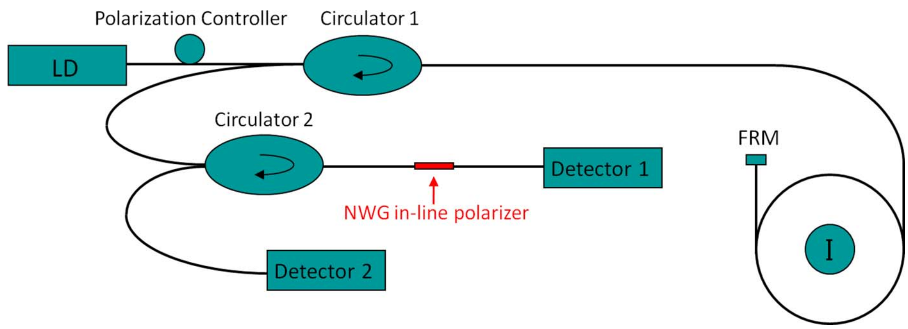

Fig. 3. Schematic of an optical fiber current sensor based on an NWG in-line polarizer. An FRM is connected at the end of the fiber coil.

obtained. Although the current contrast ratios still need further improvement in comparison with a commercial Wollaston prism, further experimental results will show that our NWG polarizer is still suitable for current sensing and could achieve good heterodyne data result.

We use the packaged fiber NWG polarizer to build up an all-fiber current sensor. Fig. 3 shows the schematic diagram. The 1550-nm light from a tunable laser (Agilent 81940A) is controlled by a fiber polarization controller to obtain any state of polarization. The light enters into the sensing unit through a circulator. The current sensing unit contains 420 fiber loops and 60 electric wire loops, which are surrounded by each other. A 45° Faraday rotation mirror (FRM) is connected by the other end of the fiber loops, for it cannot only reflect light backwards but also reduce the linear birefringence effect in the SMF, which is detrimental to the sensing [26], [27]. Then, the reflective light from the sensing unit enters into the NWG in-line polarizer. Detector 1 collects the transmitted light, and Detector 2 collects the reflection from the NWG through another circulator. The initial polarization of the light is set to be 45° linear polarized with respect to the NWG to achieve the highest sensitivity. While the linear birefringence is only negated from Circulator 1 to FRM and back, and not between Circulator 1 and NWG, we should keep the fiber between them short and stable to avoid the linear birefringence caused by elastic-optic effect.

The principle of the current sensor is based on Faraday effect. The rotation of the polarization azimuth angle θ induced by a magnetic field H is given by

$$\theta = V \int_l H dl \tag{3}$$

where V is the effective Verdet constant of optical fiber, and l is the interaction length. According to the structure of our sensing unit, (3) becomes

$$\theta = 2 V N_f N_w I \tag{4}$$

where N_f is the number of optical fiber loops, N_w is the number of electric wire loops, and I is the current flowing in the electric wire. As the current I changes, the polarization azimuth θ of light entering into the NWG changes accordingly; then, the intensities of the reflected light I_{ref} and transmitted light I_{trans} measured by two detectors can be expressed by

$$I_{ref} = I_0 \sin^2\left(\theta + \frac{\pi}{4}\right), \quad I_{trans} = I_0 \cos^2\left(\theta + \frac{\pi}{4}\right) \tag{5}$$

where I_0 is the input light intensity. As the rotation of the polarization azimuth θ is normally small, we approximate that $\sin\theta \approx \theta$, so from (5), θ can be given by

$$\theta = \frac{I_{ref}}{I_0} - \frac{1}{2}, \text{ or } \theta = \frac{1}{2} - \frac{I_{trans}}{I_0} \tag{6}$$

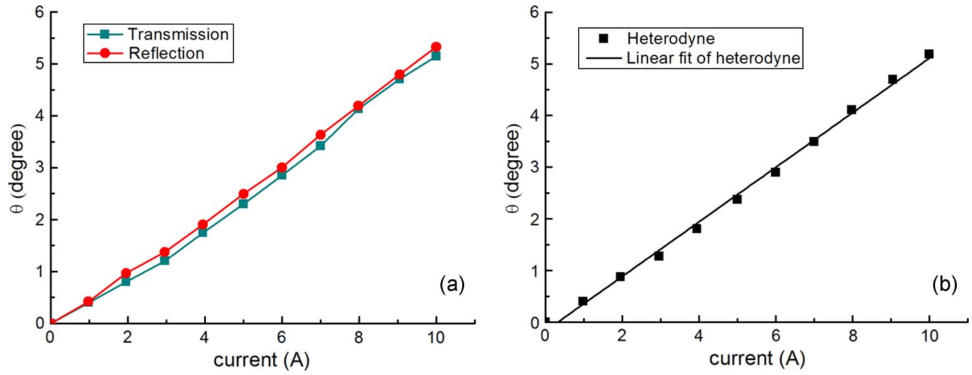

Fig. 4. (a) The measured rotation of the polarization azimuth angle θ as a function of the current value I, from both transmission and reflection. (b) The heterodyne result.

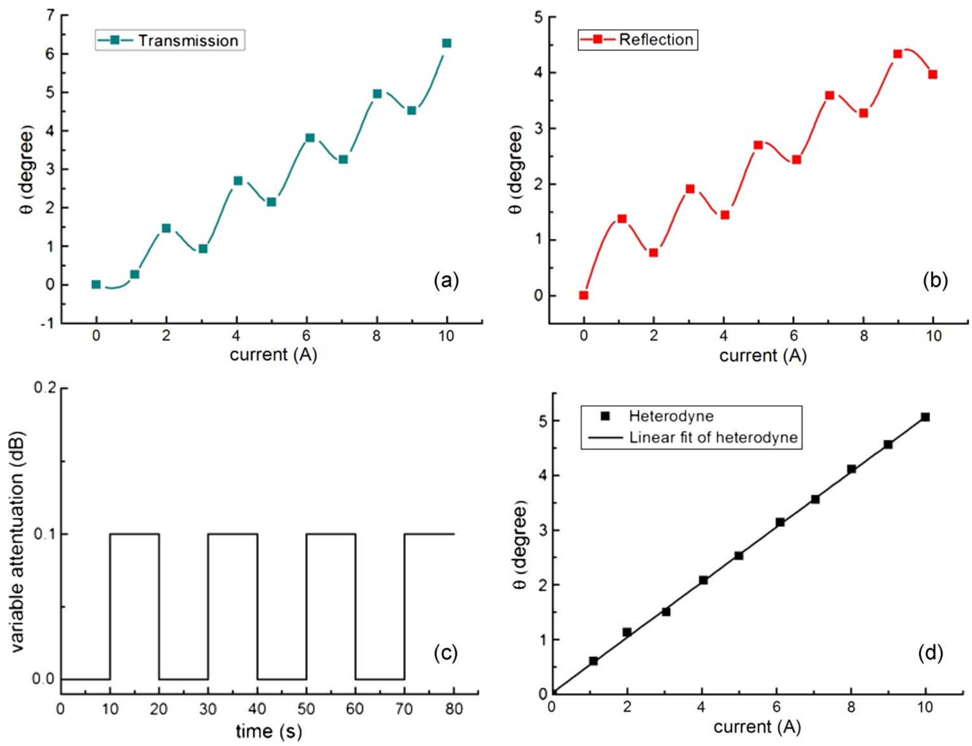

Fig. 5. The measured polarization rotation angle θ as a function of the current value I under input power variation for (a) transmitted and (b) reflected lights, respectively. (c) The light attenuation variation as a function of time. (d) The polarization azimuth θ as a function of current value I after heterodyne data treatment.

Fig. 4(a) shows the experimental results of θ's change with current I according to the transmission and reflection measurement, respectively.

If we record both reflection and transmission output change synchronously, after heterodyne data processing:

$$\frac{I_{ref} - I_{trans}}{I_{ref} + I_{trans}} = \sin(2\theta) \approx 2\theta \quad (7)$$

The result is independent with the input light intensity I_0. Fig. 4(b) shows the heterodyne sensing results according to (7). The linear fit of the experimental data gives a sensitivity of $0.528^\circ/\mathrm{A}$.

To further demonstrate the advantage of heterodyne analysis based on the transflective feature of the NWG, we mimic the unstable environment with a power fluctuated light source. We add a variable optical attenuator (EXFO 3100) into the sensing system between the tunable laser and the polarization controller. The variable attenuator gives additional light attenuation to the input light I_0. It works according Fig. 5(c). The light attenuation varies between 0 and 0.1 dB every 10 s. We change the current value and collect the sensing data from two detectors at the time 5 s, 15 s, 25 s, etc. Fig. 5(a) and (b) shows the relation between the polarization azimuth rotation θ and current value I measured respectively from two detectors. Inspection of the figures of these bending curves shows that light instability brings serious error to sensing result. However, after the heterodyne data processing according to (7), Fig. 5(d) still shows nice linear-type response, ignoring the influence of light power instability.

However, the robust response shown in Fig. 5(d) is intrinsically from the heterodyne analysis that also exists in conventional current sensors by using Wollaston prism for polarization beam splitting. In comparison with bulky free-space polarization handling components, our NWG supplies an all-fiber solution that should be principally more reliable in various practical applications. Actually, the NWG in-line polarizer could not only be used in these polarimetric sensing devices but is also applicable in other fiber-optic systems to replace normal in-line polarizers. For example, the interferometric demodulation technique is also an effective fiber-based reliable solution for current sensors [28]. Being different from the polarization azimuth angle measurement in our experiment, the current-induced polarization-dependent phase shift is recovered by means of polarization interference. If there is no initial phase difference, a π phase shift gives rise to the final detected intensity from 0 to 1. This range and intrinsic sensitivity is just similar to the polarization measurement, where a pure π phase shift may result in 90° polarization rotation and maximum intensity change. From this point of view, the interferometric and polarimetric demodulation techniques do not show much difference in sensitivity as long as an identical sensing head is used. From [28], two in-line fiber polarizers are used to distinguish two orthogonal waves. However, if our NWG in-line polarizer is used instead, maybe one polarizer is enough due to its transflective feature. In other words, the NWG should be compatible with both interferometric and polarimetric demodulation techniques showing some advantages over both bulk polarization splitter and traditional in-line polarizers.

4. Conclusion

We propose an all-fiber optical current sensor by using an NWG in-line polarizer. A simple and compact packaging approach of the NWG polarizer is developed. The final sensing system is composed of all-fiber elements, with no bulky optical component. It shows good intrinsic reliability in principle, which is much desired in practical applications. In addition, the unique NWG in-line polarizer makes the sensing process have a self-heterodyned function. Experimental results show it can withstand light variation. Theoretically, not only the light variation but also many adverse environmental factors, such as temperature instability and sensing unit vibration, could be eliminated by this compacted heterodyne sensing system.

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