Opto-Electronics Review 26 (2018) 24–28

Contents lists available at ScienceDirect

Opto-Electronics Review

journal homepage: http://www.journals.elsevier.com/opto-electronics review

Dual-resonance long-period grating in fiber loop mirror structure for liquid refractive index measurement

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ARTICLE INFO

Article history:
Received 19 September 2017
Received in revised form
20 November 2017
Accepted 23 November 2017

Keywords:
Optical engineering
Polarization-maintaining fiber
Dual-resonance long-period grating
Fiber optics sensors
Fiber loop mirror

ABSTRACT

An interferometric structure based on a Dual-Resonance Long-Period Grating (DRLPG) within a Fiber Loop Mirror (FLM) is presented in this paper. Its purpose is to measure the refractive index (RI) of liquid analytes. The grating is the RI sensing probe, while the FLM serves as a band-pass filter. Due to the high extinction ratio of the FLM, amplitude measurements can be obtained, allowing implementation of the differential interrogation method to establish the sensitivity of the device. The use of a polarization controller makes it possible to fine-tune the interferometric peaks with respect to the two notches of the DRLPG. Precisely aligned configuration produces a maximum sensitivity of 3871.5 dB/RIU within the RI range of 1.3333 up to 1.3419 with linear sensor response.

1. Introduction

Long Period Gratings (LPGs) have become very popular as platforms for chemical [1], biological [2] and physical [3,4] sensors because of their low cost, compact size and insensitivity to ambient electro-magnetic fields [5]. In recent years, different fiber configurations based on LPGs for liquid refractive index (RI) detection have been described [6], which were characterized by a very high sensitivity to resonant dip shifts caused by changes in the surrounding refractive index (SRI) [7]. This excellent sensitivity of LPGs is achieved by coupling of a guided fundamental mode to higher order cladding mode. This phenomenon leads to the appearance of two resonance peaks created by the transfer of energy to the same cladding mode at two discrete wavelengths [8]. In other words, there are two modes with identical group velocities in the LPG under conditions that lead to a broadband mode conversion [9]. When the sensing probe is exposed to an ambient perturbation, the phase matching condition changes. For this reason, the two resonant notches of the LPG shift in opposite directions [10] and thus, the sensor can work close to the turning point of the dispersion curve [11], where the sensitivity is ultrahigh [12].

RI sensors in interferometric configuration have been widely described, where the RI sensitivity part has been obtained by modification of polarization maintaining (PM) fiber. Zhong et al. [13] proposed a refractometer formed by insertion of two sections of PM fiber with different lengths, with one of the PM fibers chemically etched and used as a sensing part. Wang et al. [14] presented a compact structure of an in-line Mach-Zehnder interferometer made by femtosecond laser micromachining that achieved sensitivity of 9370 nm/RIU within the RI range between 1.31 and 1.335. Modulation in the resonant condition causes spectral shifts of both LPG notches. Since the dual-resonance long period grating (DRLPG) has a very low extinction ratio, the sensitivity response cannot be expressed by a true-amplitude modulation. Chu et al. [15] present the design of a sensor for RI measurement using a high-birefringence fiber loop mirror (HB-FLM) concatenated with the LPG. A major goal in that paper was measurement of the intensity demodulation by simple use of an optical power meter (OPM). The authors achieved a maximum LPG sensitivity level expressed in transmission intensity of 103.2 dB/RIU.

In this paper, for the first time to authors knowledge, a new approach to liquid RI sensor based on a DRLPG inside a FLM compared to previously proposed [16–18], in which the sensitivity level is expressed by the intensity is presented. Paper demonstrates that the inherent state of polarization of the propagating beam enables

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https://doi.org/10.1016/j.opelre.2017.11.002
1230-3402/

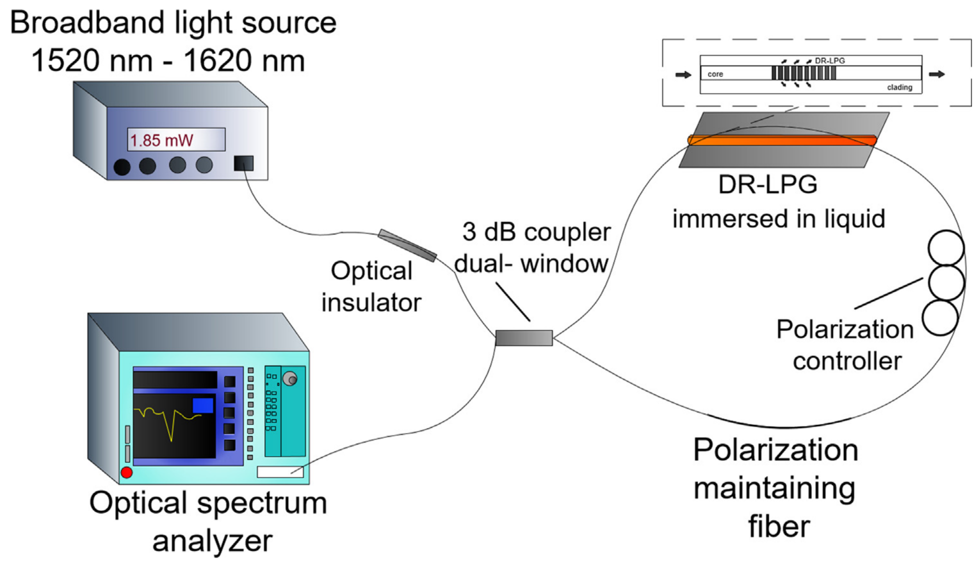

Fig. 1. Experimental set-up of the DRLPG inside an FLM for accurate liquid refractive index measurement.

adjustment of peaks which come from the FLM and the DRLPG. Placing the DRLPG inside the FLM makes it possible to implement a differential interrogation method with a sensitivity of an order of magnitude higher than in other configurations. The combination of these two optical components overcome limitations related to the low extinction ratio of the DRLPG, so that the grating acts as a broadband true-amplitude modulator of the refractometer. These two discrete properties underpin the design of the device proposed here, the FLM-DRLPG, whose amplitude of peaks is changed for an arbitrary small variation of the ambient refractive index (ARI).

2. Theory and experimental set-up

The main relation describing resonance wavelength coupling of the guided core mode and the mth cladding mode in an LPG is given as [19]:

$$\lambda_{eff}^{m} = \left(n_{eff}^{0,1} - n_{eff}^{0,m}\right) \cdot \Lambda \tag{1}$$

where, $n_{eff}^{0,1}$ is the effective RI of the propagating fundamental mode, $n_{eff}^{0,m}$ is the effective RI of the mth cladding mode and Λ is the grating period.

The scheme of the proposed FLM-DRLPG configuration is presented in Fig. 1. The FLM consists of a wideband 3 dB coupler, a section of a PM fiber – Fibercore HB 1500 (bow-tie type) – and a polarization controller (PC). A DRLPG was placed after the 3 dB coupler but before the PC. The FLM was illuminated by a broadband light source with a spectral bandwidth range from 1520 nm up to 1620 nm. An optical insulator was used to protect the optical devices against the potential instability of the propagating light. The 3 dB coupler splits the input light into two optical beams which counter-propagate around the loop and through the DRLPG, the PM and the PC. The two beams propagate with different velocities, which means that their individual state of polarization varies and the two beams interfere in the output [20]. The obtained interference pattern was monitored by an optical spectrum analyzer (OSA) with a resolution of 0.1 nm. Taking into account the operating wavelength range of the tested grating and PM fiber, the OSA spectra range was from 1520 nm to 1620 nm. However, in a future application, the OSA could be replaced by an OPM, provided the transmission spectrum of the FLM-DRLPG was fine-tuned and appropriately filtered. Hence, comparing proposed FLM-DRLPG sensor structure with sensor based on only LPG or DRLPG, the FLM-DRLPG is less expensive due to the possibility of replacement of an optical spectrum analyzer by the simple power meter, which is much cheaper.

In this experiment the DRLPG was made by an amplitude mask technique using a high-power KrF Excimer laser (Lumonics^{TM} Lasers: Pulse Master $^{®}$-840) emitting at 248 nm [21]. A section of bare fiber (Corning SMF28) was exposed to UV radiation through a chromium amplitude mask with a pitch of $\Lambda = 217\,\mu$m, which ensured coupling of the fundamental mode to a mode higher than the $LP_{0,11}$ cladding mode. Excitation of a double resonance was thus achieved. The peak pulse energy of the excimer laser was 340 nJ. After this, the LPG was annealed at a temperature of 150 °C for 90 minutes in order to release the excess hydrogen. The transmission spectra of the DRLPG was optimized by reducing the cladding diameter through partial etching with 10% Hydrofluoric acid (HF 10%) [22].

In order to match the fringe pattern to the notches of the DRLPG, the length of the PM fiber must be accurately determined. Knowing the distance between notches of the DRLPG, which was 17 nm, and taking into account the birefringence value of the PM fiber as well as the central operating wavelength of the sensor (1550 nm), the length L of PM fiber from the formula [23] is calculated as:

$$L = \frac{\lambda^2}{B\Lambda_\lambda} \tag{2}$$

where B, Λ_λ and λ are respectively the group modal birefringence of the PM fiber, the distance between notches and the operating wavelength.

The computed length of the PM fiber was 0.31 m. Fig. 2 shows the transmission spectra of the tuned FLM-DRLPG structure so that both notches of the resonance peaks are exactly covered by interference dips.

The PC was inserted between the DRLPG and the section of PM fiber to tune the transmission spectra of the FLM. This possibility was mentioned in Ref. [13], although the authors of that work provided no details. The interference peaks could be moved up to 9 nm by changing the state of polarization (SOP) of the propagating beam as well as the amplitude for about 11.25 dBm (Fig. 3).

Since the dual resonance of the LPG is visible on the transmission spectra within the specified ARI, the interference peaks have to be adjusted for the appropriate sensor range. In other words, the interference peaks should be tuned right before both notches of