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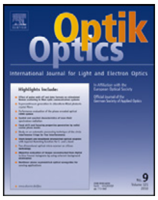

Simultaneous spectral recovery of long-period grating sensor array using optical time-division multiplexing

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ABSTRACT

A novel sensor network based on optical time-division multiplexing (OTDM) is proposed and demonstrated for simultaneous sensing of long-period grating (LPG) sensor array with overlapping spectra. A star network is configured by pairing a circulator with each of the LPG sensors. Experiments are conducted by measuring the changes of surrounding refractive index at different sensors, which show excellent agreement between the demultiplexed and pristine transmission spectrum of the LPG sensors.

1. Introduction

Long-period gratings (LPGs) have had significant impact on recent development of fiber optic sensing. Based on refractive index (RI) sensing, the application range of LPGs extends to biomedical and chemical sensing. Many coatings for LPG that can improve or even initiate sensitivity to certain selected chemical [1–4] and biological [5] influences are actively reported in these few years. Besides coating the LPGs, variety of techniques to enhance the sensitivity of LPG have been developed, which include dual resonance LPG [6], off-resonance LPG [6], fiber-taper seeded LPG pair [7], etched dual LPGs [8], and sandwiched LPGs [9].

A diversity of LPG enhancement is vigorously reported yet technique for multiplexing LPG sensors is scarcely available. The major problem encountered in multiplexing LPG is due to wide loss-band of LPG spectral response whereby common multiplexing technique for fiber Bragg grating (FBG) devices, namely wavelength division multiplexing (WDM), is not compatible to multiplex large scale of LPG sensors [10,11]. Consequently, the important criteria in the design of sensor multiplexing system are to allow wideband (linewidth of tens of nanometers) or identical sensors to share the same transmission fiber without compromising the sensing information. To the best of our knowledge, the low-coherence interferometric technique [11] and sub-carrier multiplexing (SCM) [12] are the only schemes being reported for multiplexing an array of LPG sensors. However, the low-coherence multiplexing system is highly integrated with a particular design of LPG. On the other hand, the SCM technique requires the utilization of external optical modulators, which are costly and induce additional insertion loss. On these accounts, new alternative multiplexing schemes have become necessary to be explored.

Optical time-division multiplexing (OTDM) is a common multiplexing scheme for optical communication systems. In this paper, the OTDM scheme is exploited, for the first time, in an LPG sensor array to enable recovery of individual spectrum of multiplexed sensors. We demonstrate a sensor network in star topology that is capable to sense ambient refractive index change at different locations simultaneously. The system is evaluated by comparing the pristine spectrum with the demultiplexed spectrum and performing variance analysis.

2. System setup and principle

Fig. 1 shows the system setup of OTDM for LPG sensor array. In this design, a tunable laser source (TLS) is programmed to sweep across the bandwidth that covers the loss-band of the LPGs at resolution of 0.5 nm. The polarization state of light is adjusted using a polarization controller before being launched into an electro-optic modulator (EOM). At the EOM, the light is externally modulated in response to a 10 MHz pulse signal with 4% duty cycle, fed from a pulse generator. The pulse train is subsequently amplified by an erbium-doped fiber amplifier (EDFA) to increase the extinction ratio of the pulse train to more than 21 dB. Next, an isolator is placed after the EDFA to prevent unwanted feedback from the reflected

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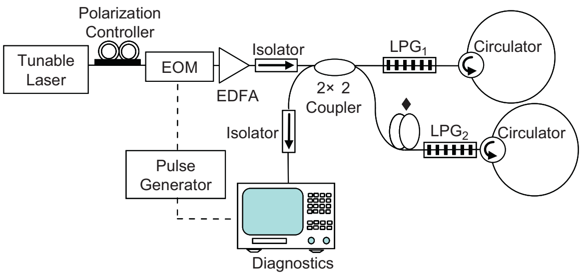

Fig. 1. System setup of OTDM for LPG sensor array.

pulses. The coupling of the amplified optical pulse train into two channels is done by using a 3 dB coupler, wherein the channels consist of identical LPG sensors. The pulse train is then attenuated by the LPG, variably corresponding to the scanning wavelength at TLS. At the end of each channel, a circulator is connected to serve as a broadband mirror. The circulator has two of its ports interlinked, thus effectively reflects the entire spectrum of sensing signal, which is further attenuated by the same LPG. In our setup, channel 2 (CH2) is delayed from channel 1 (CH1) by using a fiber with an effective refractive index, $n \approx 1.46$ and a length, $l = 4.62$ m. As the CH2 is delayed by a delay time, τ, both of the reflected sensing signals are spaced with a time interval of 2τ. Using the relation $\tau = nl/c$, where c is the speed of light in vacuum, the pulse spacing, 2τ is about 45 ns, as illustrated in Fig. 2.

For every single scanning wavelength, a data acquisition device is used to collect the peak-to-peak power of sensing signal of both channels concurrently with the aid of digital sampling oscilloscope. It is worthwhile to note that the amplitude of spectral response recorded at the data acquisition equipment is doubled with respect to the amplitude of pristine spectral response due to double passing through the same LPG. Therefore, the true amplitude of the demultiplexed spectral response is calculated to be half of the amplitude of the recorded data.

3. Experiment results and discussions

Prior to implementing the sensing experiment, the system is calibrated by scanning the spectral response of the system without the LPG sensors. By doing this, the acquired spectrum is essentially the background spectral response of the system, which is contributed by all system components. From observation, both channels exhibit almost identical background spectral responses with apparent ripples that are caused by the interference effect due to the back reflection from optical components such as coupler and circulator. Once the background spectral response is acquired, the LPG sensors are inserted in the system as shown by Fig. 1. Throughout the experiment, each of the demultiplexed spectral response is normalized with the respective background spectral response, thus nullify the appearance of the ripples.

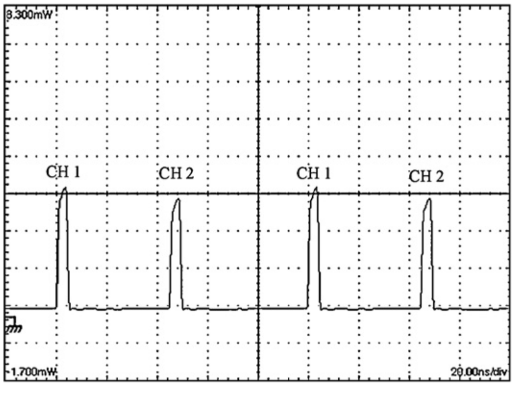

Fig. 2. Multiplexed pulse train at the output of the OTDM system at 1530 nm.

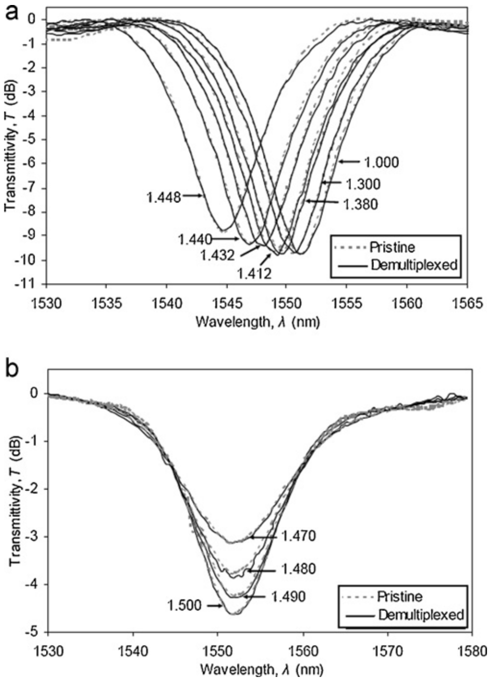

Fig. 3. Pristine and demultiplexed spectral response of LPG sensor at CH1 for various RI which is (a) lower, and (b) greater than that of the cladding.

An experiment is conducted to recover the spectral response of LPG immersed in Cargille oil with different RI values at room temperature of 24 °C. The LPG sensors located at both of the channels are sharing the same design profile in terms of bandwidth, transmission loss, and resonance wavelength, which are 9 nm, 10 ± 0.3 dBm, and 1551.75 nm, respectively. In the initial experiment, the LPG sensor at CH1 is tested with RI from 1.300 to 1.500, while CH2 serves as a reference channel. Fig. 3(a) shows the pristine and demultiplexed spectral response of LPG sensor at CH1 for RI of 1.000, 1.300, 1.380, 1.412, 1.432, 1.440, and 1.448.

In order to study the fitting of two sets of samples, the determination coefficient, r^2 can be used as a measure of discrepancy between them. In this paper, the r^2 percentage is used to indicate the resemblance between the pristine transmittivity, T and the demultiplexed transmittivity, $\hat{T}$. This parameter is calculated as follows:

$$r^2 = 1 - \frac{\sum_i (\hat{T}_i - T_i)^2}{\sum_i (T_i - \bar{T})^2} \tag{1}$$

where $\bar{T}$ is the mean pristine transmittivity.

Generally, r^2 greater than 0.8 is regarded as indicating high resemblance between two variables. The calculated r^2 percentages of the demultiplexed spectral response with respect to the pristine spectral response are 99.79%, 99.95%, 99.97%, 99.40%, 99.88%, 99.88%, and 99.89%, respectively. Hence, this OTDM system shows a very high degree of resemblance for RI lower than that of the cladding. The results in Fig. 3(b) are spectral responses of LPG at RI values greater than that of the cladding which are 1.470, 1.480, 1.490, and 1.500. From the variance analysis, the r^2 percentages of the data are 99.79%, 99.81%, 99.87%, and 99.82%, respectively. Overall, this system shows high degree of resemblance of the demultiplexed data with respect to the pristine spectral response,

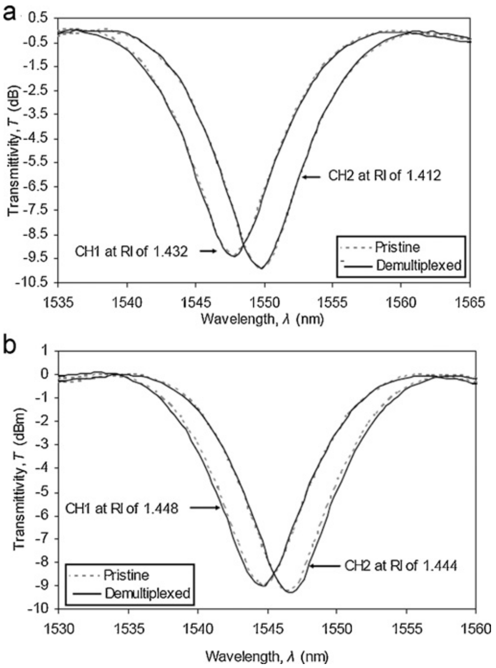

Fig. 4. Pristine and demultiplexed spectral response of LPG sensors at (a) CH1 and CH2 with RI of 1.432 and 1.412, respectively (b) CH1 and CH2 with RI of 1.448 and 1.444, respectively.

not only at RI lower than that of the cladding but also RI greater than that of the cladding.

Subsequently, to demonstrate the complete performance of OTDM sensor system, both LPG sensors at CH1 and CH2 are immersed in Cargille oil with different RI. In the first test, spectral responses of LPGs at RI of 1.412 and 1.432 are well recovered, which precisely matched their corresponding pristine spectral response, as shown in Fig. 4(a). For the spectra comparison at RI of 1.412, the r^2 percentage is 99.97% while at RI of 1.432, it shows a r^2 percentage of 99.96%. In the second test, Fig. 4(b) shows that the LPG sensors at both channels exhibit good agreement between the pristine and demultiplexed spectral responses at RI of 1.444 and 1.448, in which the r^2 percentages are 99.67% and 99.88%, respectively.

The work emphasizes on the versatility of the sensing system that permits the use of sensors with identical specifications at all sensing locations. This in turn will allow economical mass manufacturing of the sensors that will eventually lead to dramatic reduction in the retail price. Moreover, the sensors used in the network can be substituted with variety of LPGs that are available in the market, without affecting the integrity of the sensing system.

4. Conclusions

An optical time-division multiplexed LPG sensor network in star topology has been proposed. Regeneration of individual sensor spectrum from overlapping spectra was able to be performed by this system, producing a determination coefficient, r^2 of at least 99.4%. This implies that the RI characters can be accurately discriminated from different sensing LPG channels. This system offers a very attractive feature, such that the spectra regeneration is performed simultaneously. In addition, the system structure and interrogation are simple, and provides high signal-to-noise ratio sensor signal.

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