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High spectral range, high speed fiber optic spectrometer

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ABSTRACT

Fiber optic sensors have been developed recently. Among them, some encompass high speed and the others broadband spectral response. Newly, high-speed fiber-optic spectrometer (HSFOS) has been investigated. Operation of this type of spectrometer is based on conversion of spectral-domain signal into time-domain by a dispersive element. In spite of the high speed, the HSFOS supports only a narrow frequency band of the incoming light. In this paper, we used adequate photonic crystal fiber (PCF) as dispersive fiber in forming the measured spectrum from a nano-cavity sensor in order to improve the HSFOS spectral range. Spectral range enhancement of the spectrometer by means of PCF was also studied. Simulation results show that the increment of spectral range decreases the speed of spectrometer; therefore a trade-off between spectral range and speed is studied.

1. Introduction

An optical spectrometer is used as an instrument measures the spectral density of input light over a certain part of the electromagnetic wavelengths. Optical spectrometers have wide application in signal demodulation of interferometric and grating-based fiber-optic sensors. In these systems, the output signals are the spectrum of broadband lights from a sensor that recorded by spectrometer [1,2].

Several techniques have been developed in spectrum measurement of optical signals [3]. The most well-known technique utilizes a dispersive device, e.g. a prism or diffraction grating which separates different wavelengths, spatially. Then, a single detector or array of detectors is used to realize spectrum measurement at the output of the spectrometer [3]. Some spectrometers are using a tuned narrow bandpass filter to scan the input signal spectrum. In order to recover the spectral density of the incoming light, Fourier transform based spectrometers use the Fourier spectrum of the interferogram, resulting from the interferometer [4].

Earlier, high-speed fiber-optic spectrometers (HSFOS) have been reported for fiber-optic sensing applications [5]. The operational principle of the HSFOS is illustrated in Fig. 1 [6]. This spectrometer utilizes time domain dispersion of sampled incoming light by dispersive fiber rather than the spatially dispersion employed by traditional spectrometers. In this spectrometer, the incoming light signal is transmitted to modulator and then modulated by a series of narrow pulses with fixed pulse width and repetition rate from pulse generator to form time-domain samples of the light signal. These samples go away through a span of a dispersive element such as dispersive fiber so as to obtaining time domain dispersion. Each sample, after getting dispersion, gives a spectral profile which is more similar to the spectrum of incoming light. Then, the input optical signal is converted to electrical signal passing through the optical/electrical converter (O/E). The high-speed data acquisition device (DAQ) samples, digitizes each signal and then sends the data to a computer in order to produce spectrum of the input optical signals. In addition, performance improvement of the HSFOS shown in [7], describing the suitable structure for high speed and high resolution spectrometry. This spectrometer is used for new optical sensors with high speed, but supports just a narrow spectral range; however some fiber optic sensors have broadband spectral range. The use of nanostructure fiber optic sensors is increasing due to the several advantages such as shorter response time, broadband spectral range and enhanced sensitivity; whereas for optical sensors with a broadband spectral range, the mentioned spectrometer cannot be used. This is consequence of the paucity of a large and flat dispersion in a broad spectral range for SMF and DCF fibers, which are used in HSFOS. In order to enhance the spectral range and the spectrometer response speed, also to meet future requirements, we propose HSFOS with adequate photonic crystal fiber prevailing flat and large dispersion parameter in a large spectral range.

This paper is organized as follows: in Section 2, schematic and sensing mechanism of high spectral range fiber optic sensors is derived, in Section 3, the spectral range improvement of the

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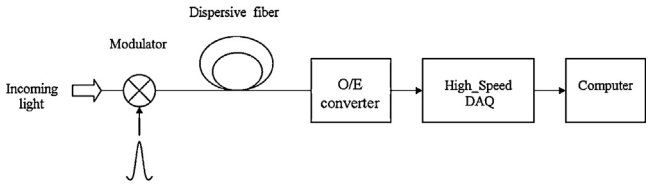

Fig. 1. Schematics of operational principle of the HSFOS [6].

spectrometer using a photonic crystal fiber is demonstrated and trade-off between the spectral range and the speed is explained and finally, in Section 4, the paper ends with a conclusion.

2. Sensing mechanism of nanostructure fiber optic sensors

This section describes the sensing mechanism of a broadband optical fiber gas sensor that its output coupled to HSFOS. The schematic structure of the sensor is illustrated in Fig. 2. In the sensor, different coating materials which are used to form interferometric cavities reflect different amount of optical power. The capture of Dichloromethane drops on the coating makes change in the reflected optical power. The change in the reflected optical power is caused by the affinity of Dichloromethane to a polymer coating composed of poly (Diallyldimethyl ammonium chloride) (PDDA) and the dye Poly S-119 [8]. The reflectance, R, of a multilayer grating shown in Fig. 2 is expressed at [9,10].

Each cavity introduces a phase shift in the electromagnetic signal that depends on the refractive index and thickness of the coating materials. The combination of these cavities forms an optical filter.

Based on the model, the theoretical reflectivity of structures (a)–(d) of Fig. 2 are shown in [8]. As predicted, in the sensing, the reflected power decreases while the number of coated layers increases.

3. Spectral range enhancement in the HSFOS

According to [6], the relationship between output and input power in the HSFOS of Fig. 1 is given by:

$$s(t) = \int_{-\infty}^{+\infty} \frac{P_t(0, t_d)}{\beta_{2t}(t_d)L} M(L, t, t_d)dt_d \quad (1)$$

where

$$\beta_{2t}(t_d) = \beta_2(\omega')$$

$$P_t(0, t_d) = P(0, \omega').$$

The term t_d denotes delay time for each light pulse when propagating through the dispersive fiber and is a function of ω'which is the central circular frequency of the modulation light pulse. $P(0, \omega')$ is the input spectrum to the spectrometer that should be measured and $\beta_2(\omega')$ denotes the second order dispersion parameter of the dispersive fiber. $M(L, t, t_d)$ is the single wavelength light pulse broadened by the dispersive fiber that is a function of t_d and denotes at different time points t_d or equivalently at different circular frequencies or wavelengths, the broadening amount of the monochromatic light pulse could be different. The amount of broadening for each modulation pulse in propagation through dispersive fiber is determined by second, third and higher order dispersion parameters which are β_2, β_3, etc. respectively [6].

The output of the spectrometer as a function of wavelength is described by:

$$s_\lambda(\lambda) = \int_{-\infty}^{+\infty} P_n(0, t_d)M_\lambda(L, \lambda, t_d)dt_d \quad (2)$$

where $s_\lambda(\lambda)$ is the spectral density function of incoming light

$$M(L, t, t_d) = M(L, \lambda, t_d)$$

Since the output of the spectrometer, $s(t)$ or $s_\lambda(\lambda)$ is the superposition of all the broadened and delayed monochromatic light pulses, it can be obtained the spectrum of input signal if the wavelengths of these pulses be in the range of the spectrometer frequency range.

The location of each monochromatic light pulse in the time domain is determined by group delay $\beta_1(\omega')L$. The existence of enough interval time among the monochromatics is necessary for exact spectrometry. In order to reduce the measurement error and have a broadband spectrometry, the GVD of the fiber in the HSFOS should not have different signs in the measurement spectral range, i.e., the β_1 of the fiber is monotonously increasing or decreasing parameter so that the lights with different wavelengths are delayed according to light frequency or wavelength fluctuation. Under this condition, $s_\lambda(\lambda)$ represents the spectrum of the input light, acceptably.

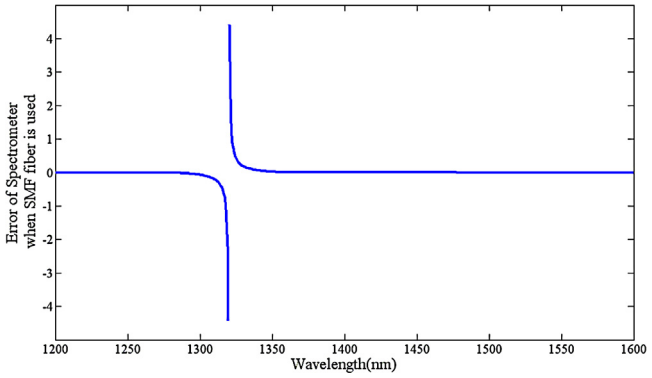

Fig. 3. The error of broadband spectrometry when SMF is used as dispersive fiber in HSFOS.

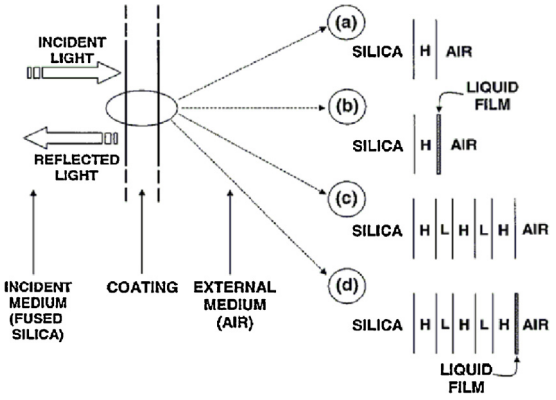

Fig. 2. Schematics of four broadband coating structures that used in simulation [8].

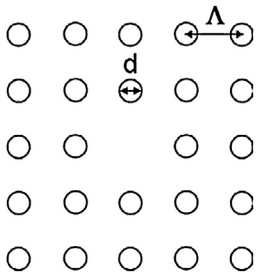

Fig. 4. Cross section of the square-lattice PCF used in the fiber optic spectrometer [12].