Intensity-modulated fiber Bragg grating sensor system based on radio-frequency signal measurement

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An intensity-modulated, fiber Bragg grating (FBG) sensor system based on radio-frequency (RF) signal measurement is presented. The RF signal is generated at a photodetector by two modulated optical signals reflected from the sensing FBG and a reference FBG. Wavelength shift of the sensing FBG changes intensity of the RF signal through changing the delay between the two optical signals, with temperature effect being compensated automatically by the reference FBG. It also exhibits important features including potentially high-speed measurement, low cost, and adjustable sensitivity. In the experiment, strain measurement with a maximum sensitivity of $-0.34\ \mu V/\mu\varepsilon$ has been achieved. © 2008 Optical Society of America

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Intensity-modulated fiber-optic sensors have attracted significant interest due to their many advantages including simplicity and potential low cost [1,2]. A large number of parameters can be measured by these sensors with the use of inexpensive light sources and simple detection schemes while still benefiting from the intrinsic advantages of photonic sensors. However, most fiber-optic sensors based on fiber Bragg gratings (FBGs) are not intensity but wavelength modulated. To monitor the reflection wavelength of FBGs, expensive wavelength measurement instrument, such as FBG interrogators based on wavelength-scanning lasers, tunable filters or CCDs, are normally used. The measurement speed of wavelength measurement instrument is relatively low and typically it is less than 1 kHz. On the other hand, intensity-modulated FBG demultiplexing systems can operate at much higher speeds. To realize intensity-modulated FBG sensors, several different techniques have been reported. By using an edge filter or a matched FBG [3,4], wavelength shift of FBG can be converted into intensity variation. However, this method allows only limited wavelength measurement range and may suffer from the so-called cross-sensitivity problem because FBGs are sensitive to both strain and temperature and the two effects are not distinguished by the sensing system. Chirped FBGs may also be used as intensity-modulated sensors by encoding the sensing information into their reflection optical power [5,6]. They are insensitive to temperature but only applicable to a few measurands that change chirp rates of the sensing FBGs.

In this Letter, a novel intensity-modulated FBG sensor system that measures parameters through wavelength shift as well as being insensitive to temperature is proposed. The sensor system is shown in Fig. 1. It consists of a broadband light source intensity modulated by a radio frequency (RF) signal, a circulator, a sensing FBG, a reference FBG, and a long length of standard single-mode fiber used as a dispersive medium. Signals reflected from the two FBGs are measured with a photodetector. Since wavelengths of the two FBGs are different and overlap is avoided, there is no optical interference present in the system.

Assuming that the intensity of the broadband light source is sinusoidally modulated at frequency f and the modulation index is m $(0<m\leq 1)$, the powers reflected from the reference and sensing FBGs can be expressed as

$$P_{r,s}=P_{r,s}^{c}[1+m\sin(2\pi ft+\varphi_{r,s})], \tag{1}$$

where P_r^c and P_s^c are optical carrier powers and φ_r and φ_s are electrical phases for the reference and sensing signals, respectively. For the convenience of analysis, we neglected the variation of P_r^c and P_s^c caused by grating wavelength shifts, and assumed $P_r^c=P_s^c=P_c$, which is reasonable when a relatively flat broadband light source is used and wavelength shifts of the two

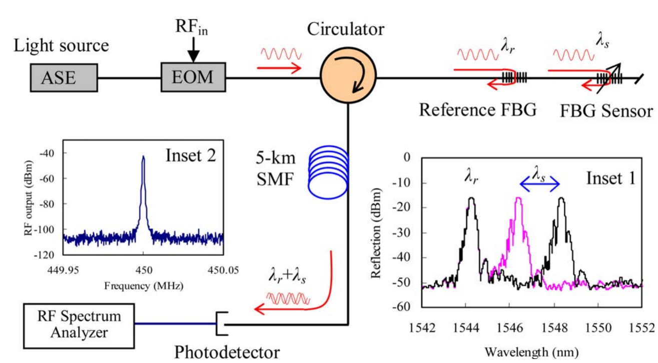

Fig. 1. (Color online) Schematic of the proposed FBG sensor. Inset 1 is reflection spectra of the reference and sensing FBGs when different strains were applied. Inset 2 is the measured RF output spectrum at 450 MHz of the sensor system.

FBGs are not very large. Optical signals at the detector will be

$$P_{\text{out}} = P_r + P_s = 2P_c + P_o \sin(2\pi f t + \varphi_o), \qquad (2)$$

with

$$P_o = \sqrt{2} m P_c [1 + \cos(\Delta\varphi)]^{1/2}, \qquad (3)$$

where P_o and φ_o are, respectively, the power and phase of the output RF signal. $\Delta\varphi = \varphi_s - \varphi_r$ is the phase difference between the sensing and reference signals and it can be expressed as

$$\Delta\varphi = 2\pi f(2n\Delta L/c + DL\Delta\lambda), \qquad (4)$$

where n is the refractive index of the fiber; c is the speed of light in vacuum; ΔL is the fiber separation between the two FBGs; and D and L are the chromatic dispersion and length of the dispersive fiber, respectively. The fiber separation between the two FBGs and the length of the dispersive fiber can be altered to adjust the initial phase difference between the reflected signals.

Since the power of the output RF signal P_o is dependent on $\Delta\varphi$ and the latter is related to $\Delta\lambda$, one can measure wavelength shift of the sensing FBG by detecting the variation of P_o (thus $\Delta\lambda$ can be determined). The effect of temperature can be eliminated by locating the two FBGs in close proximity to each other to make the wavelengths of the sensing and reference FBGs shift by the same amount in response to temperature variation (so that the wavelength separation is not influenced). This is feasible even if the sensing FBG is glued onto the surface of a structure whose thermal expansion coefficient is different from that of the glass fiber, because one can always glue the reference FBG to a piece of the same structure material and keep it free from strain.

In the experiment, an erbium-fiber-based amplified spontaneous emission (ASE) broadband source, with a high and flat power spectral density of −10 dBm/0.06 nm (0.06 nm is the wavelength resolution of the measurement setup) at around 1550 nm, was modulated by an electro-optic modulator (EOM). Because the EOM is a polarization-dependent component, a polarizer and a polarization controller were used to optimize the modulation contrast of the light source. Two 1 cm long FBGs with reflectance of ~95% at wavelengths of 1544.2 and 1544.7 nm, bandwidths of ~0.2 nm were used as the reference and sensing FBG, respectively. The center-to-center separation between them was 21 cm. Strain was applied on the sensing FBG only. Inset 1 of Fig. 1 shows the measured reflection spectra of the two FBGs when different strains of 1100 and 2200 $\mu\varepsilon$ were applied on the sensing FBG. The reflection powers of the reference and sensing FBGs are nearly the same, and the latter remain almost unchanged during the wavelength shift. A 5 km long standard single-mode fiber ($D \approx 17$ ps/nm/km) was used as the dispersive medium. A photoreceiver with low and high 3 dB cutoff frequency at 30 kHz and 1 GHz, respectively, was used as the photodetector. Inset 2 of Fig. 1 shows a measured RF signal output spectrum of the sensor system when the modulation frequency was 450 MHz and $\Delta\lambda$ was 2 nm. A high signal-to-noise ratio of ~60 dB was achieved.

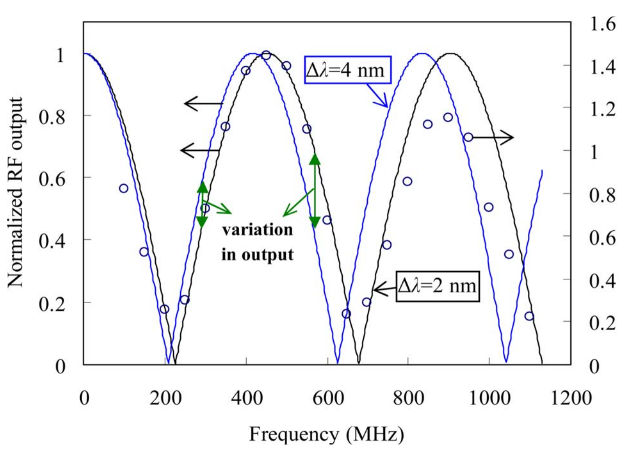

Fig. 2. (Color online) RF signal power against modulation frequency (curves: calculated results; circles: measured results for $\Delta\lambda = 2$ nm).

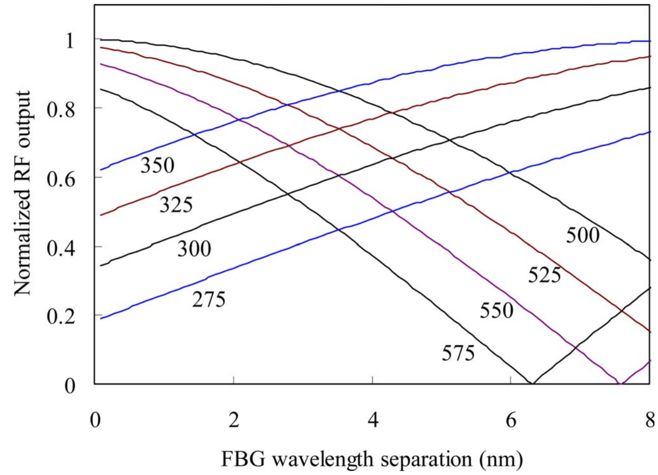

Fig. 3. (Color online) Calculated RF signal power against FBG wavelength separation for different modulation frequencies of 275 to 575 MHz.

Based on Eq. (3) and the experimental parameters given above, we can calculate the output RF signal power P_o, normalized by the maximum value, as a function of modulation frequency f when FBG wavelength separation $\Delta\lambda$ is changed, as shown in Fig. 2, where the two curves were obtained when $\Delta\lambda$ is 2 and 4 nm, respectively. It clearly shows that for a given modulation frequency, P_o changes with $\Delta\lambda$ and that its sensitivity depends significantly on the modulation frequency. Generally speaking, the higher frequency yields higher sensitivity than the lower frequency. Figure 3 shows the calculated RF output for several different modulation frequencies when wavelength separation $\Delta\lambda$ is changed continuously over a wide range. It can be seen that the sensor response is so dependent on the modulation frequency that negative and positive sensitivities can be achieved at different frequencies. An important feature of this novel FBG sensor system is that the dynamic range and sensitivity can be optimized easily by simply adjust-

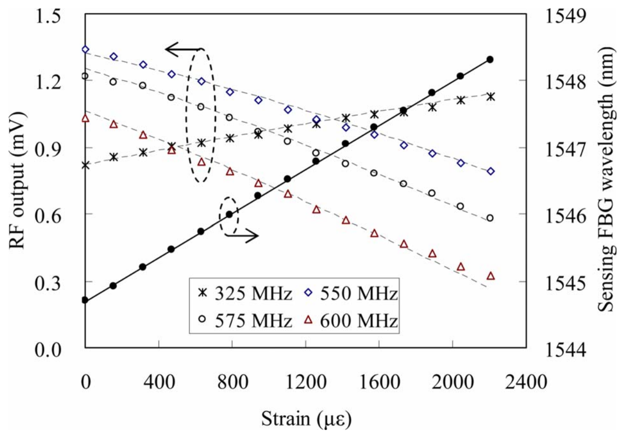

Fig. 4. (Color online) FBG wavelength shift and RF signal power (data points for measurement results; dashed curves for theoretical results) for strain measurement at different modulation frequencies.

ing the modulation frequency. There is a trade-off between the two parameters.

When strain was applied on the sensing FBG, wavelength separation between the two FBGs was changed and the output RF signal was measured with a RF spectrum analyzer. The frequency dependence of the RF signal power was measured at $\Delta\lambda = 2$ nm, as shown by circles in Fig. 2. It agrees well with the calculated results except that the power is reduced by ~20% on the low and high frequency edges. This was mainly caused by the decreased sensitivity of the photoreceiver in those frequency regions. The RF output of the sensor, as well as the wavelength shift of the sensing FBG, in response to the applied strain from 0 to 2200 $\mu\varepsilon$ was shown in Fig. 4. The wavelength of the sensing FBG increased from 1544.7 to 1548.3 nm at a rate of 1.6 pm/$\mu\varepsilon$ and the linearity is good. The sensor RF output was measured at different frequencies of 325, 550, 575, and 600 MHz. The measurement results agree well with the theoretical responses, which are shown in the same figure with dashed curves. The maximum sensitivity based on the measurement data is up to -0.34 μV/$\mu\varepsilon$, achieved at 600 MHz.

The strain measurement resolution is determined by the power level of the light source and noise of the RF signal measurement. The noise can be reduced by repetitious measurement and averaging; however, increasing the averaging time will slow down the measurement speed. So, there is a trade-off between the resolution and measurement speed. In our experiment, the measurement time, depending on several settings of the RF spectrum analyzer, including the frequency scanning range, resolution, and repeat times is in the level of tens of microseconds. However, it can be greatly reduced to much less than 1 ms by using a fixed modulation frequency and specifically designed RF measurement device. The repeatability and stability of the sensor output is good in the laboratory environment. However, fluctuations of the light source power (if any) and transmission fiber loss caused by bending or whatever may change the sensor output, P_o, through the carrier power, P_c, as indicated in Eq. (3). A possible method to compensate this effect is to measure the "dc" output signal of the photodetector, i.e., the "$2P_c$" term in Eq. (2), as a reference. This part of the work is ongoing and will be reported on in our further studies.

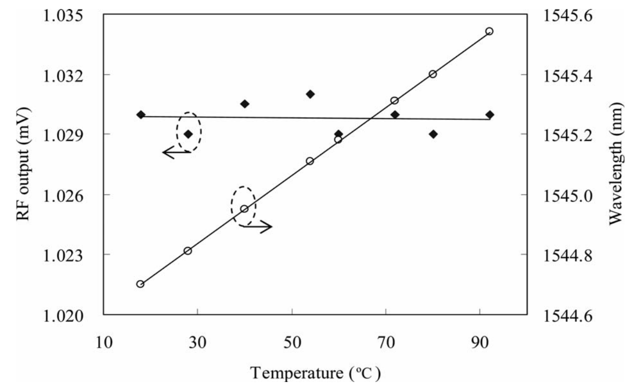

Fig. 5. Measured RF signal power against temperature.

Temperature dependence measurement was also implemented. In this experiment, both the sensing FBG (without strain) and the reference FBG were placed into a temperature-controlled chamber. The temperature was increased from 18°C to 92°C and both the wavelength of the sensing FBG and the output RF signal power were measured. The wavelength increased linearly by 0.84 nm while the RF signal power remains almost unchanged as shown in Fig. 5. The maximum deviation from the average value of the RF signal power is ~0.14%, mostly caused by the noise and reading error of the RF spectrum analyzer.

In conclusion, we have proposed and demonstrated a novel intensity-modulated, FBG sensor system based on RF signal measurement. Wavelength shift of the sensing FBG can be measured through output power of an RF signal generated by the two modulated optical signals reflected by the sensing and reference FBGs. It is worth noting that in many FBG applications, two FBGs are commonly used to measure strain with one of the FBGs strain-free for temperature compensation. In our proposed system, the strain-free FBG could act as the reference FBG. This sensor system exhibits several important features, including potentially high-speed demodulation, low cost, adjustable sensitivity, and temperature compensation.

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