

Performance Evaluation of Phase-OTDR Sensing System Based on Weak Fiber Bragg Grating Array

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We present a performance analysis of a phase-OTDR sensing system based on the concatenation of identical low-reflective fiber Bragg gratings. The performance limit of the proposed system has been investigated by means of simulations to identify the influence of the design parameters, such as FBG reflectivity, dynamic range, spatial resolution and SNR.

Introduction

Among vibration sensing methods, phase-sensitive Optical Time Domain Reflectometer (Phase-OTDR, or Φ -OTDR) has been considered as a powerful technique, thanks to its ability in both characterizing and localizing a vibration or acoustic phenomenon present along a long-distance optical fiber [1]. The great potential in adapting this technology in many fields such as seismic, oil well, and railway trackside monitoring systems, makes Φ -OTDR implementations an active research area [2]. As an alternative approach to observing the variations on the Rayleigh backscattering signal as realized in a standard Φ -OTDR system, the use of an array of fiber Bragg gratings (FBGs) acting as artificial scattering centers (having known reflectivity and position) has been attracting great interest, as this new scheme improves the signal to noise ratio (SNR) and provides high-precision dynamic strain measurement capability [3,4]. When a FBG array is interrogated, the corresponding Φ -OTDR trace presents several interference regions created by the reflection signals coming from neighboring FBGs. This signature can be used to detect any phase variation appearing between two FBGs, as long as the resolution cell (RC) of the interrogator ranges from L (distance between two successive FBGs) to $2L$ (not to cover a third FBG) [5].

In the present work, a sensor scheme based on equally-spaced, low reflectivity FBGs interrogated by direct detection Φ -OTDR has been theoretically studied and experimentally implemented. The tradeoff between the maximum number of gratings and grating reflectivity has been analyzed by simulations.

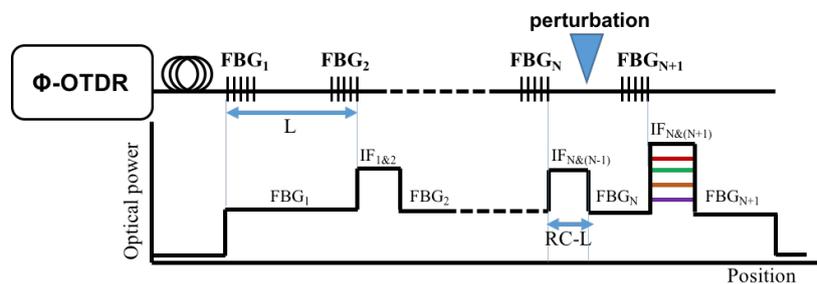


Fig.1. Proposed sensor scheme of $(N+1)$ cascaded FBG sensors, including power levels of the corresponding Φ -OTDR signature.

Theoretical analysis and simulation results

In the proposed sensor scheme, shown in Fig.1, an equally spaced concatenation of $N+1$ identical FBGs are illuminated by optical pulses (of width W) injected by the Φ -OTDR. When the resolution cell (of width $RC=W/2$) is greater than the distance L between two successive FBGs in the array, the reflected signals coming from two successive FBGs cause interference over trace

sections (represented as IF in Fig.1) of a particular length equal to RC-L. These interference sections together with the zones between them (where the signal is reflected from only one FBG) form the Φ -OTDR signature.

Let us analyze one of these interference sections, $IF_{N\&N+1}$ created by the superposition of the electric fields \mathbf{E}_N and \mathbf{E}_{N+1} (i.e. optical signals reflected from FBG_N and FBG_{N+1}). The complex reflection coefficient, \mathbf{r}_N , and the complex transmission coefficient \mathbf{t}_N for FBG_N are determined as a function of known parameters, namely grating length, grating pitch, and average refractive index modulation [6]. Given a complex electric field \mathbf{E}_{in} at the Fiber Under Test (FUT) input, the electric fields \mathbf{E}_N and \mathbf{E}_{N+1} can be represented as

$$\mathbf{E}_N = \mathbf{E}_{in} T^2(t) \mathbf{r}_N(t) \quad (1)$$

$$\mathbf{E}_{N+1} = \mathbf{E}_{in} T^2(t) \mathbf{t}_N^2(t) \mathbf{r}_{N+1}(t) e^{-i\Delta\phi(t)} \quad (2)$$

where $T(t)$ is the complex transmission coefficient of the FUT between its input and FBG_N and $\Delta\phi(t)$ is twice the phase difference between FBG_N and FBG_{N+1} . The detected power corresponding to this region can be calculated as

$$\begin{aligned} P_{N\&(N+1)} &= (\mathbf{E}_N + \mathbf{E}_{N+1})(\mathbf{E}_N + \mathbf{E}_{N+1})^* = \\ &= |\mathbf{E}_{in}|^2 |T(t)|^4 |\mathbf{r}_N(t)|^2 + |\mathbf{E}_{in}|^2 |T(t)|^4 |\mathbf{t}_N(t)|^4 |\mathbf{r}_{N+1}(t)|^2 + \\ &2|\mathbf{E}_{in}|^2 |T(t)|^4 |\mathbf{t}_N(t)|^2 |\mathbf{r}_N(t)| |\mathbf{r}_{N+1}(t)| \cos(\Delta\phi(t) + \theta(t)) \end{aligned} \quad (3)$$

where $\theta(t) = \arg(\mathbf{r}_{N+1}(t)/\mathbf{r}_N(t))$. When a perturbation is applied somewhere along the FUT, it may result in fiber strain and/or a local change in refractive index. In our simulations, (3) has been implemented based on the setup of Fig.2. (a), where the first perturbation (SHR1) is applied on FBG_4 , while the second one (SHR2) influences the fiber section between FBG_5 and FBG_6 . The vibration induced by the shakers was simulated by introducing local variations in the effective refractive index. If the perturbation is directly applied on the FBG (e.g. FBG_4 in Fig.2. (a)), the \mathbf{r} and \mathbf{t} coefficients of the FBG changes, which will lead to a change in phase relative to the neighboring FBGs (as observed for the zones $IF_{3\&4}$, FBG_4 , and $IF_{4\&5}$ in Fig.2. (b)). For a perturbation applied on the fiber section between two FBGs (e.g. between FBG_5 and FBG_6 in Fig.2. (a)), the result will be a modulation of the phase difference $\Delta\phi(t)$ between the two FBGs (as noted for the $IF_{5\&6}$ zone in Fig.2. (b)). Fourier analysis of the Φ -OTDR signature at the perturbation-influenced positions over many successive measurements (i.e. slow-time analysis) allows determining the frequency content of the perturbation.

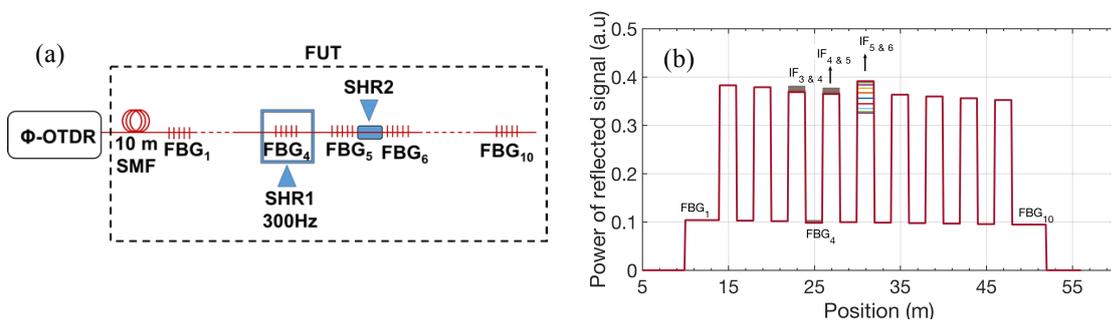


Fig.2. (a) Simulated sensor scheme, (b) successive simulated Φ -OTDR traces for $N=10$, two perturbations are applied: directly on FBG_4 , and on the fiber section between FBG_5 and FBG_6 . SHR: Shaker.

Experimental investigations and measurement results

Experimental work has been carried out to validate the vibration frequency extraction scheme. A direct detection Φ -OTDR was used to interrogate ten cascaded FBGs that were placed after a lead

fiber of 1.5 km. The center wavelength of each identical FBG is 1552.5 nm with the bandwidth of 0.2 nm (wide enough to make the sensor insensitive to 200 $\mu\epsilon$ of strain and 20 $^{\circ}\text{C}$ temperature changes). The gratings used in the sensor were manufactured with G.657 single mode fiber (Draka BendBright), with an effective refractive index of 1.4471) using Noria FBG manufacturing facilities (phase mask technique). Re-coating was not made after inscription. The FBGs had a length of 4 mm, a grating periodicity of 535 nm and an average refractive index modulation of $\sim 10^{-5}$. The reflectivity of the FBGs was 0.02%. In the Φ -OTDR interrogator, a highly coherent laser having 0.1 kHz linewidth, 40 mW continuous output power and a center wavelength of 1552.51 nm was modulated by an acousto-optic modulator (applying a frequency shift of 160 MHz) to emit probe pulses with a repetition frequency of 20 kHz. The pulses were amplified by an EDFA, followed by a 0.9 nm bandpass filter. The reflected signature of the FBG array was detected using a photo-receiver with a 5 MHz electrical bandwidth, and the detected signal was sampled by a 1 GHz digitizer. 1850 consecutive traces were recorded for each measurement resulting in a slow-time window (the total measurement time, given as the number of pulses times the pulse separation) of about 90 ms. The fiber section between FBG₅ and FBG₆ was glued onto a 2 m long, 16 mm diameter plastic tube that was clamped at both ends. The distance between the FBGs was 4 m, and consequently the resolution cell should be chosen between 4 m and 8 m. The measurements were therefore made with a pulse width of PW= 60 ns, corresponding to a 6-m resolution cell. Perturbations were applied at two different positions as indicated in Fig.2(a): A shaker SHR1 was used to apply 300 Hz, 1 g acceleration vibrations on FBG₄, while the midpoint of the plastic tube between FBG₅ and FBG₆ was excited by shaker SHR2 giving an acceleration of 0.1 g at frequencies 1 – 6 kHz.

A reference trace was taken with PW=10 ns to determine the FBG positions in the FUT (cf. Fig.3. (a), only the last 60 m section of the FUT including the 10 FBGs is shown for the sake of simplicity). Fourier analysis performed on the particular zones of the OTDR signature reveals the frequency components of the applied vibrations. The frequency of shaker SHR2 can be identified in the IF_{5&6} zone (at the position 32 m in the analyzed section shown in Fig.4. (a)), while the frequency of shaker SHR1 has been observed in three different sections (IF_{3&4}, FBG₄, IF_{4&5}). The FFT analysis performed in the FBG₄ zone is shown in Fig.4. (b).

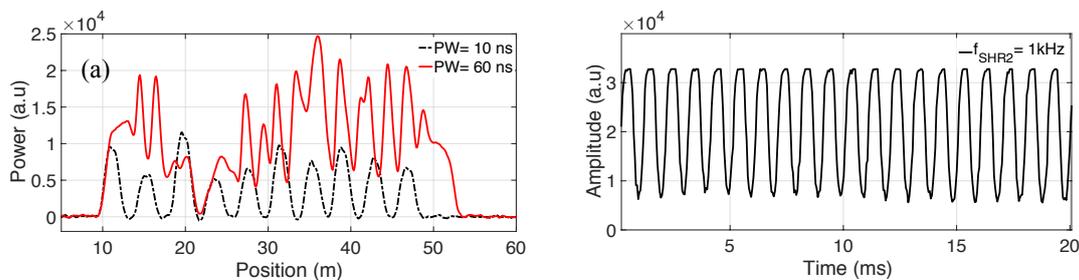


Fig.3. (a) Comparison of experimental traces for the pulse-widths of 10 ns (RC=1 m) and 60 ns (RC=6 m), (b) variation of Φ -OTDR trace over slow-time window (zoomed at 0-20 ms portion) at 32 m (IF_{5&6}).

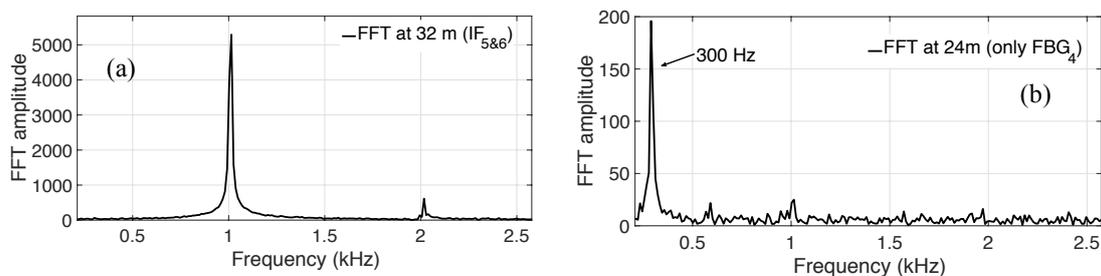


Fig.4. (a) FFT at 32 m for IF_{5&6}, (b) FFT at 24 m for the FBG₄-only reflection zone.

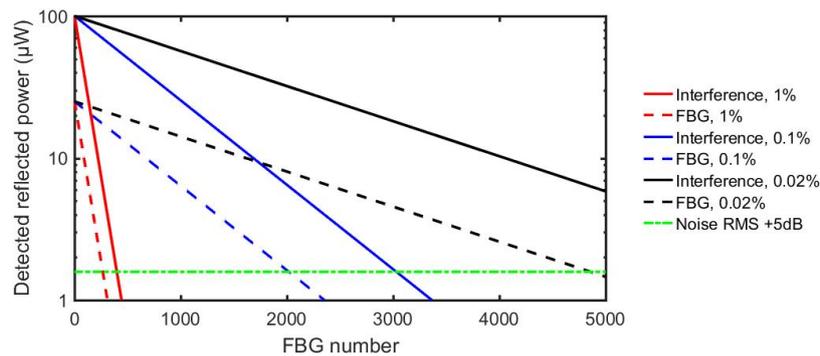


Fig.5. Maximum number of FBGs possible to interrogate with the setup using 0.02%, 0.1% and 1% reflectivity FBGs, respectively.

Given the present Φ -OTDR system with a maximum detectable reflected power of 100 μW , a fiber loss of 0.2 dB/km, an FBG reflectivity of 0.02% and an experimental RMS noise level of 0.50 μW , the theoretical number of FBGs that can be interrogated by the system can be estimated to at least 4000, maximizing the dynamic range of the system and having more than 5dB margin to the RMS noise level (see Fig. 5).

This maximum number of FBGs is based on identical FBGs inscribed along the fiber, assuming no splices or connectors along the way giving additional loss, and also assuming that the pulse quality is good enough for the 5dB noise margin to enable power detection from the last FBG. It is also based on the fact that not only all the interference powers but also the reflected powers from all individual FBGs should be able to read out. Under the same conditions, a setup with identical 1% (0.1%) reflectivity FBGs results in a maximum of 250 (2000) FBGs in the array.

Conclusions

A direct detection Φ -OTDR is used to interrogate equally spaced, ultra-low reflectivity FBGs. The presence and the frequency content of the perturbations along the FUT have been successfully monitored. Such a system having the potential for improving the SNR in phase-OTDR distributed vibration sensing is estimated to be capable of interrogating 4000 FBGs with identical 0.02% reflectivity.

Acknowledgement

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