Simulation of the performance of Phase-Sensitive OTDR Based on Ultra-weak FBG Array using Double Pulses

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ABSTRACT

A phase-sensitive optical time domain reflectometry sensing system based on Ultra-weak FBG Array using double pulses is proposed. The principle of this sensing system is elaborated. A series of simulations are carried out to optimize the parameters to increase the sensing distance of this system. The parameters contain reflectivity of UWFBG, the interval between adjacent UWFBGs and pulse width. The optimal reflectivity and pulse width corresponding to different grating space are found out to achieve a longer sensing distance.

Keywords: *Phase-sensitive OTDR, Ultra-weak FBG Array, Signal-to-Noise Ratio*

1. INTRODUCTION

Vibration sensing is an important application for distributed optical fiber sensors (DOFSs). Among all the kinds of DOFSs, phase-sensitive optical time-domain reflectometry (Φ-OTDR) has the abilities of long-distance distributed sensing, high sensitive detection to vibration and so on. As a result, it has attracted much attention and been applied to many fields [1-4].

The signal to noise ratio (SNR) of Φ-OTDR is limited by the weak Rayleigh backscattering (RBS) in fiber. In order to improve the SNR, the assistance of an Ultra-weak FBG (UWFBG) array is a potential method. UWFBG array is a recently developed technique. A few of its applications have been reported for multi-points and distributed sensing purposes [5-9]. F. Zhu has proposed a distributed Φ-OTDR system which can achieve high-precision dynamic strain measurement by sweeping the laser frequency and using unwrapping algorithms. And L. Xia has analyzed the dynamic range of the system by simulations for a fixed UWFBG interval and different number of UWFBGs [9]. However, the method uses a single optical pulse to generate interference between the reflected signals by two adjacent UWFBGs, so the pulse width should be at least twice times longer than the space interval of two adjacent UWFBGs. When the space interval is large, the peak power of the optical pulse is severely limited to avoid the nonlinear effect. Besides, since a large portion of the reflected signals cannot overlap with each other to generate effective interference signal, the long probe pulse will generate more unwanted RBS, which leads to lower SNR.

In this paper, we put forward a Φ-OTDR system in a sensing fiber integrated with an UWFBG array by using double probe pulse. Detailed simulations are made and shown that the proposed system have better performance such as higher SNR, longer sensing distance, et al. And optimal parameters are obtained for the system.

2. PRINCIPLE

The principle of the technique is shown in Fig. 1. The sensing fiber is integrated with UWFBG array which has uniform spatial interval. All the UWFBGs have the same central wavelength and the same weak reflectivity. A double-pulse is used as the probe pulse. The space interval between the two pulses equals two times distance between adjacent UWFBGs. As shown in Fig. 1, because the reflected signal and the probe pulse transmit in opposite directions, the reflected signal of the front pulse from UWFBG2 and the reflected signal of the rear pulse from UWFBG1 overlap and transmit backward together. Because the coherence length of the lightwave is much longer than the interval of the double pulse, the reflected optical signals will interfere with each other. Such a probe pulse can make the optical pulse have a higher peak power to increase the SNR without inducing nonlinear effect in fiber. The interval of double pulse can be adjusted easily to adapt any UWFBG array with uniform interval.
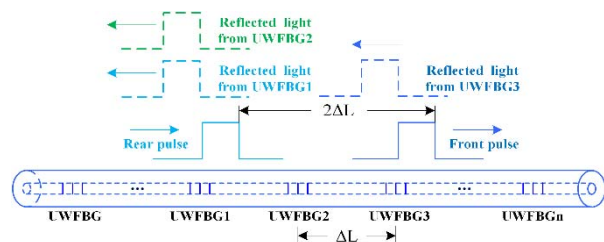

Fig. 1. The principle of the Φ-OTDR based on UWFBG array using double pulse.

When the fiber between two adjacent UWFBGs is disturbed by vibration, the refractive index n and the length of the fiber will be changed. Then the phase difference between the two reflected signals will change accordingly, which then induces the variation on the intensity of the interference. So the disturbance of fiber can be detected by detecting the intensity variation of the coherent signal.

3. SIMULATION

As is shown in Fig.1, the space interval between adjacent UWFBGs isΔL, the number of UWFBGs is n, and thus the distance between the ith UWFBG and the incoming end is $i\Delta L$. The reflectivity of all UWFBGs is approximately the same, denoted as r, then the transmissivity of UWFBGs is 1-r. The power of probe pulse isP_0, so the reflected signal of the ith UWFBG can be written as

$$P(i) = P_{Ref}(i) + P_{Ray}(i) + P_{Mul}(i) + P_{NEP} \qquad (1)$$

where $P_{Ref}(i)$ is the reflected power of the ith UWFBG, $P_{Mul}(i)$ and $P_{Ray}(i)$ are powers of the multi-reflection lightwave and the RBS respectively, and P_{NEP} is the noise-equivalent-power (NEP) of the detector. So the SNR of the detected signal is defined as

$$SNR(i) = \frac{P_{Ref}(i-1) + P_{Ref}(i)}{P_{Mul}(i-1) + P_{Mul}(i) + P_{Ray}(i-1) + P_{Ray}(i) + P_{NEP}} \qquad (2)$$

where

$$\begin{cases} P_{ref}(i) = P_0 r(1-r)^{2(i-1)} e^{-2\alpha i \Delta L} \\ P_{Ray}(i) = P_0 (1-r)^{2i} v_g \tau \alpha_R S e^{-2\alpha i \Delta L} \\ P_{mul}(i) = P_0 r^3 (1-r)^{2(i-2)} \frac{(i-1)(i-2)}{2} e^{-2\alpha i \Delta L} \end{cases} \qquad (3)$$

and $\alpha = 0.046$ km^{-1} is the fiber attenuation coefficient, v_g is the velocity of lightwave in fiber, τ is the pulse width, $\alpha_R = 3.2 \times 10^{-2}$ km^{-1} and $S = 1 \times 10^{-3}$ are the Rayleigh scattering coefficient and backscatter capture ratio of fiber respectively [9,10]. Based on Eq. (2), simulations were made to investigate the performance of the proposed system. In simulations, the NEP of the detector was assumed to be -50dBm.

Firstly, the influence of the reflectivity of the UWFBGs is given in Fig.2. It can be seen that a higher reflectivity deplete the power of the probe pulse soon, resulting in a short sensing distance. Meanwhile, a very
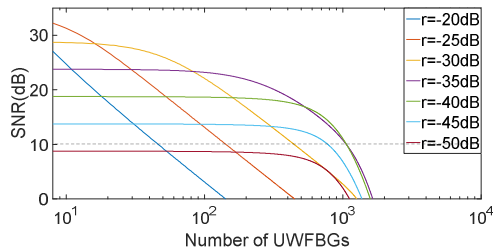

Fig. 2. The SNR evolution with the number of UWFBGs for different reflectivities. The peak power of laser is 20 dBm and the space interval is 50m.

low reflectivity will lead to low SNR and short sensing distance too since the RBS dominates in the signal. Therefore, an optimized reflectivity exists for the longest sensing distance. If we set 10dB of SNR as a threshold and make the simulation with fine steps, we find that the optimal reflectivity is – 37 dB with which the system can reach the longest sensing distance.

Moreover, we find that the optimal reflectivity also changes with the space interval of UWFBGs. Thus, we make simulations to find the relationship between the optimal reflectivity and space interval which is shown in Fig.3. It can be seen that the optimal reflectivity increases with the increase of UWFBG interval. Because when the space interval becomes longer, the loss resulted from UWFBGs' reflection decreases and the power of multi-reflections decreases too for a given length of fiber. Therefore, a stronger reflectivity is allowed to get a longer sensing distance.
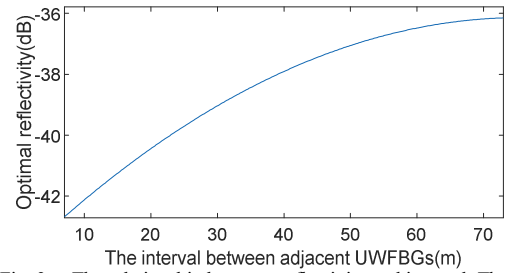

Fig. 3. The relationship between reflectivity and interval. The optimal reflectivity shows the tendency of rising with the increase of interval between adjacent UWFBGs.

Eq. (2) also shows that the pulse width can also influence the SNR. So the following simulations will focus on the influence of pulse width.

Then, the relationship between the pulse width and the SNR of the signal is shown in Fig.4. It can be seen that the SNR decreases with the increment of the pulse width in the front section of fiber. This is because a longer pulse width will generate more RBS. The SNRs for different pulse widths tend to be zero at the same distance, because the power of the probe pulse and the RBS decrease in proportion with the distance while the power of multi-reflections tends to be constant for long distance. From Fig. 4 it seems that the SNR of the
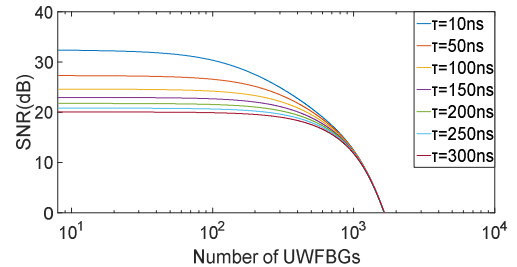

Fig. 4. The SNR evolution with the number of UWFBGs for different pulse widths

proposed technique can be improved by shorten the pulse width and increase the peak power of the probe pulse. However, we can further improve the SNR by average the signals in the same reflected optical pulse obtained with long pulse width. The SNR improvement after digital multiple-point averaging technique is $5 \lg N$

[11], where N is average number. So the SNR improvement with the average for a 100 ns pulse width is 5 dB higher than that of a 10 ns pulse width. Then the relationship in Fig. 4 is amended to Fig. 5 by considering the contribution of average.
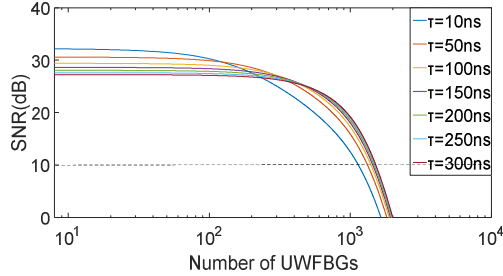

Fig. 5. The SNR evolution with the number of UWFBGs for different pulse widths with average.

During the simulations above, the peak power of the probe pulse is assumed to be constant. As is known to all, the capacity of the maximum peak power in fiber is different for different pulse widths because of nonlinear effect. Normally, the threshold of optical pulse is mainly limited by the stimulated Brillouin scattering and the threshold for different pulse width is shown in Table.1 which is obtained with the parameters in reference [12].

Table. 1   Stimulated Brillouin scattering threshold for different pulse width

Pulse width (ns)	10	50	100	150	200	250	300
P_{th} (dBm)	39.5	32.5	29.4	27.7	26.5	25.5	24.7

So in summary, the space interval, the reflectivity, the pulse width and the nonlinear effect are all contribute to the longest sensing distance of the system. And by considering all parameters mentioned above comprehensively, we finally can get the optimal parameters and longest sensing distances for different space intervals, which are shown in Table 2.

Table. 2   The longest sensing distance and pulse width corresponding to different grating space

Grating space(m)	Optimal reflectivity(dB)	Pulse width(ns)	Sensing distance(km)
10	-42.4	50	74.51
20	-40.3	10	86.52
30	-38.9	10	88.17
40	-38.1	10	91.68
50	-37.2	10	93.05
60	-36.6	50	94.32
70	-36.1	10	98.14

4. CONCLUSION

In conclusion, we carry out a series of simulations to optimize the parameters to increase the sensing distance of double pulse Φ-OTDR assisted with UWFBG array. The influences of the space interval, the reflectivity, the pulse width and the nonlinear effect to the longest sensing distance are considered in the simulation. Finally, we find out the optimal reflectivity and pulse width corresponding to different space interval to achieve the longest sensing distance.

6. REFERENCES

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