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Enlargement of Measurement Range by Double Frequency Modulations in One-Laser Brillouin Correlation-Domain Distributed Discrimination System

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Abstract: A new scheme based on double frequency modulations is proposed to enlarge the measurement range in Brillouin correlation-domain distributed discrimination system with one laser source. The measurement range is increased from ~5 m to ~34 m with the spatial resolution maintained to be 10 cm.

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Brillouin-based fiber-optic distributed sensors have been intensively studied during last decades because of their great potential applications in structural health monitoring. Recently, we demonstrated a solution to completely discriminate the strain and temperature responses by use of a polarization maintaining optical fiber (PMF) [1], where a new concept of Brillouin dynamic grating (BDG) [2] was utilized. A correlation-domain technology [3,4] and a time-domain one [5,6] were adopted to develop the distributed discrimination systems for simultaneous sensing of strain and temperature. To overcome the frequency fluctuation between/among the multiple laser sources required in [3-6], we proposed a one-laser-based system where light waves for BDG writing and reading were inherently coherent [7]. The one-laser-based system ensures precise discrimination of strain and temperature without any time-consuming averaging. On the other hand, commonly in the Brillouin optical correlation-domain analysis (BOCDA) systems, the measurement range is limited to be the distance between neighboring correlation peaks since they are not allowed to appear simultaneously in the fiber under test (FUT) [3,8]. Furthermore, the measurement range is in a trade-off relation with the spatial resolution. In this paper, we present a new scheme to enlarge the measurement range based on using double sinusoidal frequency modulations to the laser source [9].

The experimental setup is depicted in Fig. 1. As explained in [7], the modulated laser source (DFB-LD) generates the pump (probe) and readout waves for BDG generation and detection via an intensity modulator (IM1) driven by a microwave synthesizer (RF1). The pump-probe frequency offset for BDG generation as well as the Brillouin gain spectrum (BGS) measurement was precisely controlled by RF2 through a single sideband modulator (SSBM). It is new that two frequency modulations (Mod.1 and Mod.2) were simultaneously applied to the laser source. The Mod.1 with greater modulation frequency (f_m) and higher modulation depth (Δf) produces denser and narrower correlation peaks along a PMF as FUT; the Mod.2 with smaller modulation frequency ($f_m{}' = \sim f_m/7$) and lower modulation depth ($\Delta f'$) generates coarser and broader correlation peaks. By Mod.2, only one wanted correlation peak generated by Mod.1 is selected and unwanted peaks are suppressed; therefore, the measurement range is enlarged. It is noticeable that two frequency modulations are not necessarily synchronized. The distribution of BGS and dynamic grating spectrum (DGS) was continuously measured by scanning the modulation frequencies of the Mod.1 and Mod.2.

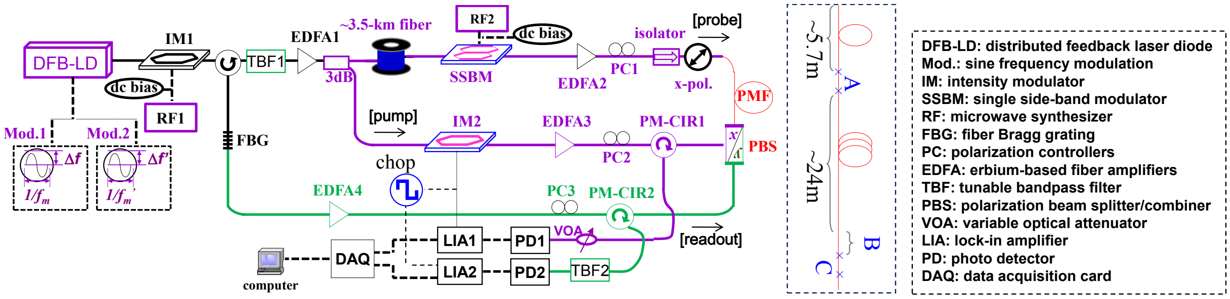

Fig. 1. Experimental setup of one-laser BOCDA discrimination system for strain and temperature based on dual frequency modulation scheme. The FUT configuration is depicted in the dashed box in the middle, and the abbreviations are explained in the right dashed box.

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Table 1 Strain and temperature applied to the FUT

Fiber positions	*A*	*B*	*C*	*Other*
Length	16 cm	80 cm	16 cm	~33 m
Strain (με)	1500	0	150	0
Temperature (°C)	40.5	45	40.5	25

Table 2 Parameters of dual frequency modulations applied to the laser source

Mod.		f_m (kHz)	Position	Δ*f* (GHz)	Δ*z* (cm)
1	BGS	20075.8- 20130.2 (64Hz step)	0-34m (4cm step)	1.0	5
1	DGS			6.0	10
2	BGS'	2945.9-3000.34 (64Hz step)	0-34m (4cm step)	1.0	34
2	DGS'			1.0	340

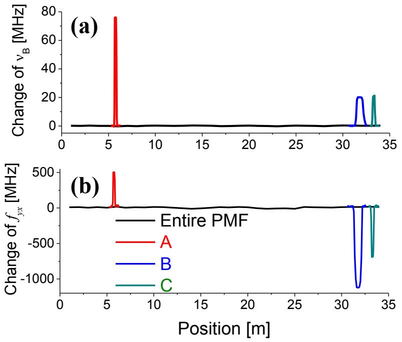

Fig. 3. Distribution of the changes of ν_B (a) and f_{yx} (b) along the ~34-m PMF where different strain/temperature are applied at three sections (*A*, *B* and *C*).

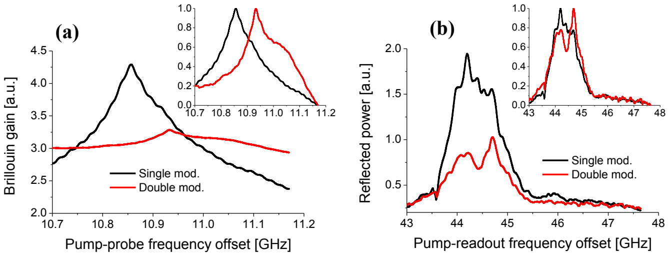

Fig. 2. Local BGS (a) and DGS (b) measured at the *A* section where 1500 με and 40.5 °C are applied. The insets show the normalized results.

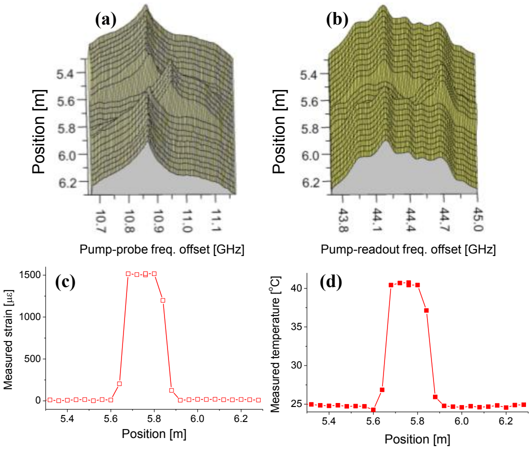

Fig. 4. Measured 3-D distribution of BGS (a) and DGS (b) around the *A* section. Distribution of discriminative sensing of strain (c) and temperature (d) around the *A* section.

The inset of Fig. 1 depicts a PMF comprising three sections (*A*, *B* and *C*) under different strain/temperature, which are summarized in Table 1. The parameters of two frequency modulations are given in Table 2. The measurement range is estimated to be ~34 m and the nominal spatial resolution is ~5 cm for BGS and ~10 cm for DGS [3]. Figure 2 shows the local BGS and DGS measured at the *A* section, which is heated by 15.5 °C and strained by 1500 με. When the Mod.2 was not applied to the DFB-LD, the changes of Brillouin frequency shift (ν_B) and the birefringence-determined frequency deviation (f_{yx}) at the *A* section could not be detected. When two modulations were applied together, those changes were successfully interrogated, showing the effectiveness of the double frequency modulation scheme. Figure 3 illustrates the distribution of the changes of ν_B and f_{yx} along the entire PMF, which were given by peak-searching of the BGS and DGS distribution, respectively. It is clear that three sections with different strain and temperature can be distinguished. For example, at the *B* section where only temperature was changed from 25 °C to 45 °C, the opposite behaviors of ν_B and f_{yx} to heating are observed. Three-dimensional (3-D) distribution of BGS and DGS around the *A* section is depicted in Fig. 4(a) and 4(b). By use of the cross-sensitive matrix [1], we calculated the strain and temperature, which are all in agreement with the setting values. Examples for the *A* section are plotted in Fig. 4(c) and 4(d).

In conclusion, we have demonstrated a new scheme to enlarge the measurement range in the one-laser BOCDA distributed discrimination system. Double frequency modulations were applied to the laser source simultaneously to suppress the unwanted correlation peaks in the FUT. The measurement range of ~34 m (enlarged by about 7 times) was experimentally achieved with the nominal spatial resolution of ~10 cm. It is expected that the new scheme will enable the BOCDA discrimination system with more feasibility as a fiber-optic nerve system in smart structures.

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