All-optical dynamic grating generation based on Brillouin scattering in polarization-maintaining fiber

Kwang Yong Song,[1,*] Weiwen Zou,[2] Zuyuan He,[2] and Kazuo Hotate[2]

[1]*Department of Physics, Chung-Ang University, Seoul, Korea*
[2]*Department of Electronic Engineering, The University of Tokyo, Tokyo, Japan*
**Corresponding author: songky@cau.ac.kr*

Received January 30, 2008; revised March 20, 2008; accepted March 20, 2008; posted March 25, 2008 (Doc. ID 92171); published April 22, 2008

We report a novel kind of all-optical dynamic grating based on Brillouin scattering in a polarization maintaining fiber (PMF). A moving acoustic grating is generated by stimulated Brillouin scattering between writing beams in one polarization and used to reflect an orthogonally polarized reading beam at different wavelengths. The center wavelength of the grating is controllable by detuning the writing beams, and the 3 dB bandwidth of ~80 MHz is observed with the tunable reflectance of up to 4% in a 30 m PMF. © 2008 Optical Society of America

OCIS codes: 050.2770, 060.2310, 190.4370, 290.5900.

A high-speed and reconfigurable dynamic grating can be used as a powerful tool in communication or sensor applications as a tunable optical filter, an optical switch, and a distributed sensor [1–4]. The currently available scheme is to build up a gain or absorption grating in an Er-doped fiber (EDF) by counterpropagating optical waves with the same optical frequency. However, such an EDF-based dynamic grating suffers a couple of significant problems, such as difficulty in separating the writing and reading beams [1,2] or an amplified spontaneous emission (ASE) noise due to optical pumping [3,4], which can give disadvantages in practical applications.

In this Letter, we demonstrate a novel kind of dynamic grating based on stimulated Brillouin scattering (SBS) in a polarization-maintaining fiber (PMF). An acoustic phonon generated by SBS between two counterpropagating writing beams of one polarization is used as a tunable and dynamic grating for the orthogonally polarized reading beam at different wavelengths satisfying the phase-matching condition. The reflected probe wave experiences an ordinary Brillouin shift by the Doppler effect, and the optical frequency difference between the writing and the reading beams is determined by the birefringence of the PMF. The basic theory, the operation principle, and the experimental configuration are described, and the results are explained using a simplified theory of Brillouin scattering.

SBS is generally modeled as a three-wave interaction between the pump (ν_1), Stokes (ν_2), and acoustic waves. When a phase-matching condition is satisfied ($\nu_1-\nu_2=\nu_B$, ν_B being the Brillouin frequency), strong energy transfer from the pump to the counterpropagating Stokes wave takes place generating acoustic waves, which stimulates the process. The ν_B is given by following equation [5]:

$$\nu_B=\frac{2nV_a}{\lambda}, \tag{1}$$

where n, V_a, and λ are the refractive index, the velocity of the acoustic wave, and the optical wavelength, respectively. In a PMF (or any medium with birefringence), optical waves with two principal polarizations (i.e., x and y polarization) experience different ν_B's owing to their different refractive indexes. Considering that the acoustic wave generated by SBS is a longitudinal one that is free of the transversal polarization [6], an interesting condition can be reached that the x- and the y-polarized optical waves in a PMF show the same ν_B at different wavelengths. When the dispersion of the acoustic wave is ignored, the condition is expressed by following equations:

$$\frac{2n_xV_a}{\lambda_x}=\frac{2n_yV_a}{\lambda_y}, \tag{2}$$

$$n_x\nu_x=n_y\nu_y, \tag{3}$$

where $n_{x,y}$ and $\nu_{x,y}$ (if $n_x>n_y$, $\nu_y>\nu_x$) are the refractive indexes and the optical frequencies in x and y polarizations, respectively. With $\Delta n=(n_x-n_y)\ll 1$ and $\Delta\nu=\nu_y-\nu_x\ll\nu$ (ν_x or ν_y), Eq. (3) is simplified to

$$\Delta\nu=\frac{\Delta n}{n}\nu. \tag{4}$$

Since the SBS-induced acoustic waves can be viewed as moving gratings for the reflection of the pump wave without polarization dependence, it is expected that acoustic waves generated by SBS between the x-polarized pump and Stokes waves at the optical frequency ν_x will show strong reflectance to the y-polarized pump wave at the frequency of $\nu_x+\Delta\nu$. Considering that the intensity and the wavelength of the acoustic waves are easily tuned by controlling the x-polarized "writing" beams, one may expect the SBS in a PMF to play a role of a tunable dynamic grating.

We composed an experimental setup, as shown in Fig. 1. For the writing of the dynamic grating, a

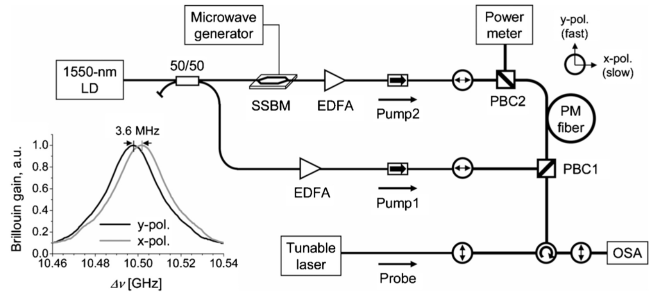

Fig. 1. Experimental setup: LD, laser diode; SSBM, single-sideband modulator; EDFA, Er-doped fiber amplifier; PBC, polarization beam combiner; OSA, optical spectrum analyzer. The inset is the Brillouin gain spectra of the fiber under test in x and y polarizations.

1550 nm laser diode was used as a light source, and the output power was divided by a 50/50 coupler. A single-sideband modulator (SSBM) and a microwave synthesizer were used to generate the Stokes wave (pump2) of the writing beams, and the output was amplified and polarized by an EDF amplifier (EDFA) and an x polarizer. The Brillouin pump wave (pump1) of the writing beams was prepared by amplifying the original wave with the same polarization as that of pump2. Pump1 and the pump2 were launched into a PMF in opposite direction to each other through polarization beam combiners (PBC1, PBC2). The PMF was a PANDA fiber manufactured by Fujikura with a 30 m length and a nominal $\Delta n \sim 6.2 \times 10^{-4}$ at the wavelength of 1300 nm. For a reading beam (probe), a tunable laser with an operating wavelength near 1550 nm was used as a light source after being polarized in the y axis. The output was launched into the PMF in the direction of the pump1 through a polarization-maintaining circulator and PBC1. The transmitted power of the probe was measured using a power meter, and the backreflected spectrum was monitored using an optical spectrum analyzer (OSA) through a y polarizer.

At first, we measured the Brillouin gain spectra of the PMF in the x and y axes. The ν_B in the x axis was measured to be 10.502 GHz, and the difference of the ν_B's of two polarizations was ~3.6 MHz, as depicted in the inset of Fig. 1, which corresponds to $\Delta n \sim 5.0 \times 10^{-4}$ by Eq. (1). To induce the SBS in the x axis, we launched pump1 and the pump2 in the x axis with the output powers of 630 and 10 mW, respectively, setting their frequency offset (Δf) to 10.502 GHz.

For the detection of the dynamic grating, the frequency of the probe was tuned at the higher frequency region while monitoring the spectrum with the OSA, and the result is shown in Fig. 2. When $\Delta\nu$ (the frequency difference between pump1 and the probe) was ~72.6 GHz, a large reflection of the probe was observed (black curve) as a result of the dynamic grating at the frequency detuned from the probe by the same amount as that between pump1 and pump2. When one of the pumps (pump1) was turned off, the dynamic grating disappeared as depicted by the gray curve although the probe was still propagated as confirmed by the Rayleigh scattering seen at the probe frequency. In both cases, the x-polarized

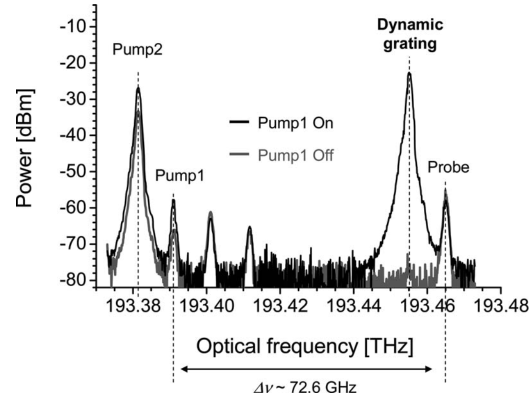

Fig. 2. Optical spectra monitored by an OSA in the generation of dynamic grating. The gray curve corresponds to the case that one (pump1) of the writing beams is turned off, and the black curve with both writing beams turned on.

pumps were observed in spite of the use of the y polarizer in front of the OSA, which originated from the finite extinction ratio (~20 dB) of the polarizing components. The small peaks near pump1 correspond to the first- and second-order anti-Stokes waves that were suppressed in the SSBM used for the generation of pump2.

Figure 3(a) shows the reflectance of the dynamic grating with respect to $\Delta\nu$, calculated from the ratio of the input and the reflected powers of the probe, while the pump powers were maintained to the same as the first measurement. The maximum reflectance was ~4%, and the 3 dB width was ~80 MHz. The overall shape looks asymmetric, which could be attributed to the irregularity of the local birefringence in the PMF.

We fixed $\Delta\nu$ to 72.6 GHz and swept Δf, the frequency offset between pump1 and pump2. The result is depicted in Fig. 3(b), which fits well with a Lorentzian curve with a 3 dB width of 28 MHz, similar to the ordinary Brillouin gain spectrum of the fiber.

The dependence of the grating reflectance on the pump powers was measured by varying one of the pump powers with the other fixed, while $\Delta\nu$ was kept at 72.6 GHz. Figures 4(a) and 4(b) show the reflectance of the grating as a function of the power of pump1 and pump2, respectively. It is remarkable that the reflectance grows in an exponential form to some definite value with the power of pump1 as

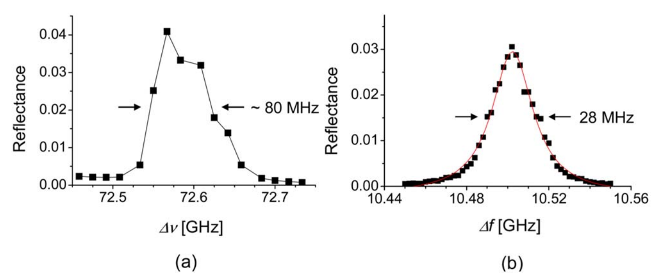

Fig. 3. (Color online) (a) Reflectance of the dynamic grating as a function of $\Delta\nu$, the frequency difference between the pump1 and the probe. (b) Reflectance of the dynamic grating at a fixed $\Delta\nu$ (72.6 GHz) as a function of the Δf, the frequency offset between pump1 and pump2. The curve shows the result of a Lorentzian fit.

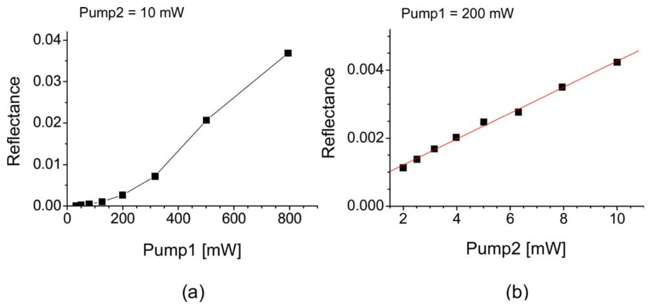

Fig. 4. (Color online) Reflectance of the dynamic grating as a function of pump power in the case of (a) pump1 varied and pump2 fixed to 10 mW, and (b) pump2 varied and pump1 fixed to 200 mW. The line is the result of a linear fit.

shown in Fig. 4(a), while it is linearly dependent on the power of pump2 as depicted in Fig. 4(b), where the result matches well with a linear fit with the slope of 3.8×10^{-4} (/mW). The slight inconsistency in the reflectance values of Figs. 4(a) and 4(b) came from long-term drift of the optical frequencies of the pump and the probe lasers, whose effect was negligible in each measurement.

The difference in dependence of the grating reflectance on the pump powers can be explained by the relation of the Brillouin gain and the reflectance. In the generation of the dynamic grating, the increased power of pump2 through the gain of the SBS can be viewed as the reflection of pump1. Additionally, we may assume that pump1 and the probe experience almost the same reflectance, since they share the same acoustic grating. Therefore, if the pump depletion is ignored (i.e., small reflection of pump1), the reflectance of the dynamic grating R can be estimated from the gain of the SBS [5] as follows:

$$R = \frac{P_{\text{probe}}^{\text{out}}}{P_{\text{probe}}^{\text{in}}} \approx \frac{\Delta P_2}{P_1} = \frac{P_2(e^{(g_B P_1 L_{\text{eff}}/A_{\text{eff}})} - 1)}{P_1}, \qquad (5)$$

where g_B, L_{eff}, A_{eff}, P_1, and P_2 are the Brillouin gain coefficient, the effective length of the fiber, the mode effective area, the power of pump1, and the power of pump2, respectively. In Eq. (5), one can see that the reflectance of the grating linearly depends on P_2, and the reflectance will grow in an exponential form according to P_1 if the gain is large enough. The final point in Fig. 4(a) with pump1 of 800 mW looks deviated from the form of the exponential growth, which could be attributed to the gain saturation with the pump depletion due to too large amplification of pump2. The reflectance offset appearing in the linearly fitted graph of Fig. 4(b) can be attributed to the amplification of the SBS noise induced by the strong pump1.

We think detailed properties of the grating can be explained by coupled wave equations (by five-wave mixing instead of the three-wave one in the ordinary case of the SBS), and there could be more factors that have an effect on the grating reflectance such as the probe power. Further research is needed on this point.

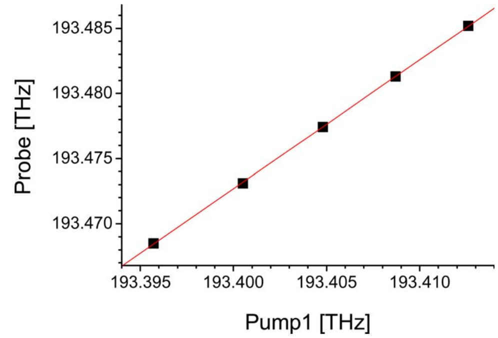

Fig. 5. (Color online) Optical frequency of the probe as a function of the frequency of pump1 under the condition of the dynamic grating generation. The line is the result of a linear fit.

The relation between the optical frequencies of pump1 and the probe under the condition of the dynamic grating generation is depicted in Fig. 5, which shows good linearity as expected from Eq. (3). In the measurement, the powers of the pumps and the probe were kept constant, and the variation of ν_B was negligible (<1 MHz).

In conclusion, we have demonstrated a novel all-optical dynamic grating based on stimulated Brillouin scattering in a polarization-maintaining fiber. The center frequency of the grating was ~72.6 GHz detuned from the writing beam frequency, and the reflectance as well as the peak frequency could be tuned by controlling the power and the frequency of the writing beam. Considering the high sensitivity of the dynamic grating to local birefringence [see Eq. (4)] as well as the high on–off extinction ratio (>60 dB), the spectral flexibility [7], and the short response time (~10 ns) [5] of the SBS, we believe the SBS-based dynamic grating has large potential for practical applications such as an all-optical switch and a highly sensitive fiber sensor.

The authors are grateful to Luc Thévenaz from EPFL in Lausanne, Switzerland, for his contribution to the development of the idea. This work was supported by the "Grant-in-Aid for Creative Scientific Research" and the "Global Center of Excellence Program" from the Ministry of Education, Culture, Sports, Science and Technology, Japan. K. Y. Song was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD) (KRF-2007-331-C00116).

References

1. S. J. Frisken, Opt. Lett. **17**, 1776 (1992).
2. B. Fischer, J. L. Zyskind, J. W. Sulhoff, and D. J. DiGiovanni, Opt. Lett. **18**, 2108 (1993).
3. X. Fan, Z. He, Y. Mizuno, and K. Hotate, Opt. Express **13**, 5756 (2005).
4. X. Fan, Z. He, and K. Hotate, Opt. Express **14**, 556 (2006).
5. G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. (Academic, 1995).
6. W. Zou, Z. He, and K. Hotate, IEEE Photon. Technol. Lett. **18**, 2487 (2006).
7. M. González Herráez, K. Y. Song, and L. Thávenaz, Opt. Express **14**, 1395 (2006).