Optics Communications 396 (2017) 210–215

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Characterization of Brillouin dynamic grating based on chaotic laser

Jianzhong Zhang[a,b,*], Zhuping Li[a,b], Mingjiang Zhang[a,b,*], Yi Liu[a,b], Yang Li[a,b]

[a] *Key Laboratory of Advanced Transducers and Intelligent Control System, Ministry of Education and Shanxi Province, Taiyuan University of Technology, Taiyuan 030024, People's Republic of China*

[b] *Institute of Optoelectronic Engineering, College of Physics and Optoelectronics, Taiyuan University of Technology, Taiyuan 030024, People's Republic of China*

A R T I C L E I N F O

Keywords:
Chaotic laser
Brillouin dynamic grating
Reflection spectrum
Gain spectrum

A B S T R A C T

The Brillouin dynamic grating (BDG) based on chaotic laser has particular advantages over the conventional BDG, for example, the creation of single and permanent BDG. To gain insight into the chaotic BDG, we theoretically investigate the reflection and gain spectra characteristics of the chaotic BDG generated in the polarization maintaining fiber. We find that the reflection spectral width of the chaotic BDG is inversely proportional to the effective grating length and the variation in the gain spectral width is negligible with respect to the effective grating length. The widths of the reflection and gain spectra are not affected by the power of the chaotic pump wave. Besides, we analyze that the occurrence of the weak BDG in the generation process of the chaotic BDG leads to the side-lobe of the reflected pulse.

1. Introduction

Stimulated Brillouin scattering (SBS), a nonlinear effect of optical fibers, usually limits the transmission power in optical fiber communication systems caused by its low threshold power, thus it is usually avoided. Conversely, SBS is used to generate Brillouin dynamic grating (BDG) in polarization-maintaining fiber (PMF) [1], single mode fiber [2], lew-mode fiber [3], photonic crystal fiber [4] and integrated chip [5]. Based on its characteristics, the BDG has been extensively applied to all kinds of fields, such as distributed optical fiber sensing without cross-sensitivity of temperature and strain [6], tunable optical delays [7], all-optical signal processing [8], and high-resolution optical spectrometer [9].

The BDG is generated by utilizing two counter-propagating pump waves along a fiber with the identical polarization and their frequency difference is set to the Brillouin frequency shift (BFS). The BDG is actually a moving periodically modulated refractive index acting like a moving fiber Bragg grating (FBG), which results from two pump waves interference giving rise to density variation associated with an acoustic wave through electrostriction effect. According to the signal format of pump waves, the generation of the BDG is further divided into two categories: time domain system and correlation domain system. In the time domain system, the pulse signals are usually used as the pump waves to generate the BDG. For one thing, the two pump waves which consist of the pulse and continuous wave (CW) signals are employed to form the BDG. However the length of the generated BDG is limited by the phonon lifetime [10]. For another, the two pump waves consisting of both pulse signals are utilized to generate the BDG. However the short BDG is periodically developed at the repetition frequency of the pump pulse, thus the reflection intensity of the BDG is unstable with time [11,12], although this scheme can break the limit of the phonon lifetime. For the time domain system, the generation of the BDG usually requires the pulse signal with very short pulse width and the peak power of several hundred Watt, which leads to complex system structure and high-cost scheme. In the correlation domain system, the BDG is generated by using two synchronous frequency-modulated CW signals [13] or two common pseudo-random bit sequences [14,15] as two pump signals. However, the periodicity of the frequency-modulated CW signal or the pseudo-random bit sequence leads to the creation of multiple BDGs, which can limit its application in tunable optical delays or all-optical signal processing. To generate a single BDG in the optical fiber, new signal format including amplified spontaneous emission (ASE) [16] or chaotic laser [17] is employed as pump waves.

Actually, chaotic laser and ASE both belong to the same kind of signal with the incoherent state since chaotic laser has the characteristics of noise-like. However, for the BDG generated by utilizing the incoherent signals, the characterization of this BDG has not been reported so far, although its generation is simply proven feasible.

In this paper, taking the chaotic BDG as an example, we deeply investigate the reflection and gain spectra of the chaotic BDG in order

* Corresponding authors at: Key Laboratory of Advanced Transducers and Intelligent Control System, Ministry of Education and Shanxi Province, Taiyuan University of Technology, Taiyuan 030024, People's Republic of China

E-mail addresses: zhangjianzhong@tyut.edu.cn (J. Zhang), zhangmingjiang@tyut.edu.cn (M. Zhang).

http://dx.doi.org/10.1016/j.optcom.2017.03.066
Received 22 February 2017; Received in revised form 25 March 2017; Accepted 27 March 2017
Available online 31 March 2017
0030-4018/

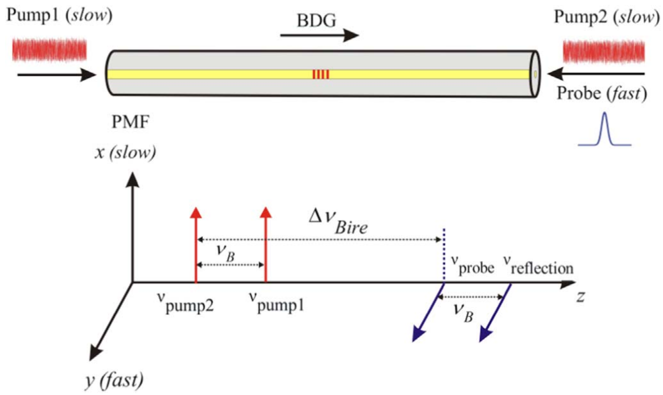

Fig. 1. Schematic diagram of the chaotic BDG generation and readout.

to gain insight into the BDG based on the incoherent signals and promote the application of this particular BDG.

2. Theoretical model

The generation and readout processes of the chaotic BDG in PMFs are shown in Fig. 1, where two identical chaotic light signals served as pump1 and pump2 are simultaneously launched into the slow axis (*x-axis*) of a PMF from both ends, respectively. When pump1 and pump2 satisfy the SBS phase-matching condition, that is, $\nu_{\text{pump1}}-\nu_{\text{pump2}}=\nu_B$ (ν_B being the BFS), stimulated Brillouin interaction between pump1 and pump2 occurs and the generated beat signal will periodically modulate the refractive index of PMF to form a chaotic BDG at the center of the PMF. In order to further analyze the characteristics of the chaotic BDG, we inject a probe pulse along the fast axis (*y-axis*) which is orthogonal to the slow axis of the PMF with the same incident direction as the pump2. When probe and pump2 satisfy the phase matching condition, that is, $\nu_{\text{probe}}-\nu_{\text{pump2}}=\Delta\nu_{Bire}$ ($\Delta\nu_{Bire}$ being PMF birefringence frequency difference), the reflectance of the chaotic BDG can be maximized.

Here, a theoretical model of the chaotic BDG is established by using the SBS five-wave coupling equation [17,18] as follows:

$$\partial_z A_{p1} + \beta_{1s}\partial_t A_{p1} = -\eta g_B Q A_{p2}, \tag{1–1}$$

$$-\partial_z A_{p2} + \beta_{1s}\partial_t A_{p2} = \eta g_B Q^* A_{p1}, \tag{1–2}$$

$$-\partial_z A_p + \beta_{1f}\partial_t A_p = \eta g_B Q^* A_r e^{i\Delta kz}, \tag{1–3}$$

$$\partial_z A_r + \beta_{1f}\partial_t A_r = -\eta g_B Q A_p e^{-i\Delta kz}, \tag{1–4}$$

$$\partial_z Q + (1/2\tau_B - i\Delta\omega)Q = (A_{p1}A_{p2}^* + A_r A_p^* e^{i\Delta kz})/2\tau_B. \tag{1–5}$$

Where A_{p1}, A_{p2}, A_p, A_r are the slowly varying envelopes of pump1, pump2, probe and reflection waves, respectively, and Q is the acoustic field generated by the electrostriction interaction in SBS process of pump1 and pump2. β_{1s} and β_{1f} are the slow and fast axis group delays per unit length. $\Delta k=(k_p+k_r)-(k_{p1}+k_{p2})$ is the phase detuning,which is directly related to the frequency difference $\Delta\nu$ of the pump 2 and probe waves, where k_{p1}, k_{p2}, k_p, k_r are the propagation constants of pump1, pump2, probe and reflection waves, respectively. To make the phase detuning Δk=0, the frequency difference between the probe and the pump2 induced by the PMF birefringence can be expressed as: $\Delta\nu_{Bire}=\nu_{\text{probe}}-\nu_{\text{pump2}}=\Delta n\nu_{\text{probe}}/n$, where $\Delta n=n_x-n_y$ is the PMF birefringence, n_x and n_y are the refractive index of the slow axis and fast axis of the PMF, respectively. $\Delta\omega=\nu_{\text{pump1}}-\nu_{\text{pump2}}-\nu_B$ is the frequency detuning of the pump1 and pump2. When $\Delta\omega$=0, we can obtain the reflection spectrum of the chaotic BDG by measuring the peak power of the reflection wave as a function of $\Delta\nu_{Bire}$. When $\Delta\nu_{Bire}$=0, we can get the gain spectrum of the chaotic BDG by measuring the peak power of the reflection versus $\Delta\omega$. The physical significance and value of other parameters of the PMF are listed in the following Table 1.

Table 1
Physical significance and value of parameters of the PMF in simulation.

symbol	Physical significance	value
L	length of PMF	1 m
Δn	birefringence	5×10^{-4}
g_B	SBS gain coefficient	5×10^{-11} m/W
τ_B	acoustic wave lifetime	5 ns
A_{eff}	effective area	40 μm^2
n_s	average refractive index of PMF slow axis	1.45
η	amplitude normalization factor	2×10^{-3} Ω^{-1}

Chaotic light can be generated by semiconductor lasers with an external optical feedback, and this simulation is theoretically described by the following Lang-Kobayashi rate equations [19]:

$$\frac{dE(t)}{dt} = \frac{1}{2}(1+i\alpha)\left[G(t)-\frac{1}{\tau_p}\right]E(t) + kE(t-\tau)\exp(-i\omega\tau), \tag{2–1}$$

$$\frac{dN(t)}{dt} = \frac{I}{qV} - \frac{1}{\tau_n}N(t) - G(t)|E(t)|^2, \tag{2–2}$$

$$G(t) = \frac{G[N(t)-N_0]}{1+\varepsilon|E(t)|^2}. \tag{2–3}$$

where E and N are the slowly varying complex electrical field amplitude and the carrier density in the semiconductor laser cavity, respectively. α, G, N_0, τ_p,τ_n,V, q are the linewidth enhancement factor, the differential gain coefficient, the carrier density at transparency, the photon lifetime, the carrier lifetime, the active region volume and the charge quantity, respectively. I is the pump current density of the semiconductor laser. ω is the output angular frequency of the semiconductor laser and τ is the external cavity round-trip time.

And the feedback rate k of the optical feedback semiconductor laser is defined as follows:

$$k = \frac{1}{\tau_{\text{in}}}\frac{(1-r_0{}^2)r}{r_0}. \tag{3}$$

where r_0 and r represent amplitude reflectivity of the laser exit facet and the external reflection mirror respectively. τ_{in} is the round-trip time of light in laser cavity. All the involved laser parameters and their values used in our numerical model are from [19].

The characteristics of the output chaotic light from the optical feedback semiconductor laser are shown in Fig. 2. Fig. 2(a) presents the time series of the chaotic light, and we can see that the chaotic signal has the characteristics of noise-like. The optical spectrum of the chaotic laser is shown in Fig. 2(b). Its spectral width is about 50 GHz by Lorentz single-peak fitting, which shows that the chaotic laser has low coherence. Fig. 2(c) shows the frequency spectrum of the chaotic signal, and its frequency spectral bandwidth is above 10 GHz. Fig. 2(d) shows the autocorrelation curve of the chaotic laser with the characteristic of the δ-like function curve.

The chaotic signals from the optical feedback semiconductor laser as two identical pump waves are injected into the PMF from its both ends. When two chaotic pump waves meet at the center of the PMF, due to their SBS interaction the chaotic BDG can be generated. In the numerical simulation, the electric field $E(t)$ of the chaotic laser is obtained by solving the Eq. (2). The acoustic wave field $Q(z,t)$ representing the chaotic BDG formation is achieved through direct integration of the Eq. (1) under the specific boundary conditions, that is, $A_{p1}(0,t)=A_{p2}(L,t)=E(t)$, $A_p(L,t)=A_r(0,t)$ =0. Fig. 3 shows the distribution of the acoustic wave field $Q(z,t)$. The three-dimensional and two-dimensional projection distribution of the acoustic wave field $Q(z,t)$ as a fuction of the time and space are further illustrated in