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Dark-Pulse Brillouin Optical Time Domain Analyzer for km-Range Detection with Only One Fiber Section

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Abstract：In dark-pulse Brillouin optical time domain analyzer (DP-BOTDA) DP-BOTDA the effective sensing length is greatly limited by the severe interaction between the Quasi-CW pump light and pump light. A simple DP-BOTDA was proposed to prolong the total sensing length without using multi-section fibers. To mitigate the impact of the high power Quasi-CW pump light，both Brillouin gain and loss effect along fiber were measured simultaneously in this scheme，yielding the Brillouin signal by subtracting the two side bands of the optical carrier suppressed (OCS) Stokes light. Based on this proposal，the total sensing length in DP-BOTDA could be increased. Simulations and discussions were conducted to validate the proposal，and the results are useful for designing high spatial resolution distributed Brillouin fiber sensor.

Key words：Brillouin optical time domain analyzer; Dark pulse，Optical carrier suppressed; Sensing length prolongation

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0 Introduction

Brillouin scattering-based distributed fiber-optic sensing is a powerful measurement tool using the inelastic scattering of incident light by an acoustic wave (phonon) to determine the strain and/or the temperature distribution along the fibers. Initially，most efforts into the related research were concentrated on extending the overall sensing range to several tens of kilometers[1-2]. Recently，there has arisen an interest in high spatial resolution sensing on shorter fibers with specific coding methods，such as pre-pumping[3-4]，double pulse[5-6]，differential pulse-width pair[7] and dark pulse[8-9] with which centimeter resolution will be easily achieved.

DP-BOTDA is one of the most attractive methods to realize below centimeters spatial resolution. Because the pulse width independence characteristic of Brillouin gain spectrum (BGS) in DP-BOTDA，millimeter-level resolution can be easily achieved [9]. However the considerable high Quasi-CW pump light power injection，greatly limits the effective interaction length (L_{eff})[9-10]. It has been reported that by concatenation of fiber sections with varying Brillouin frequencies，where each section is shorter than the threshold length for SBS，the sensing length limitation will be overcome，but it will increase the complexity of the system.

In this paper，a DP-BOTDA configuration for sensing length prolongation is proposed. With OCS format stokes light，both Brillouin gain and loss effect can be generated，and the distributed Brillouin signal will be achieved by subtracting the two detected sidebands signal. As the pump light power is the dominate factor limiting the total sensing length，based on the proposed configuration，the effect of Quasi-CW component could be greatly reduced which will prolong the total sensing length of the system.

1 Analysis and simulations

As in the Quasi-CW pumped BOTDA，the

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total sensing length is mostly limited by the power of the pump light, as equation (1) shows, for example the threshold of input stokes power is 1 mW in 20 km fiber system .

$$L_{\mathrm{eff}} \approx \frac{21A_{\mathrm{eff}}}{g_{\mathrm{B}}P_{\mathrm{P}}} \tag{1}$$

In this paper, a simple DP-BOTDA configuration is proposed in this section to revise the receiving Stokes power. In this configuration the optical carrier of the RF modulated stokes light is suppressed by MZM, before it was launched into the testing fiber remaining two side band $f_{\mathrm{C}}-f_{\mathrm{B}}$ and $f_{\mathrm{C}}+f_{\mathrm{B}}$. When the counter-propagating pump and stokes light interact with each other, the light-wave at frequency $f_{\mathrm{C}}-f_{\mathrm{B}}$, the first lower side, is amplified by pump light f_{C} to grow exponentially, while the first upper side $f_{\mathrm{C}}+f_{\mathrm{B}}$ amplifies the pump light-wave f_{C} getting significantly depletion by high power pump light. At the receiver part, the sidebands are divided by an optical DEMUX, and then detected separately. Two detected signal is used be subtracted, yielding the final distribution of the Brillouin signal.

In Fig. 1 the Stokes signal generated from the MZM can be expressed as

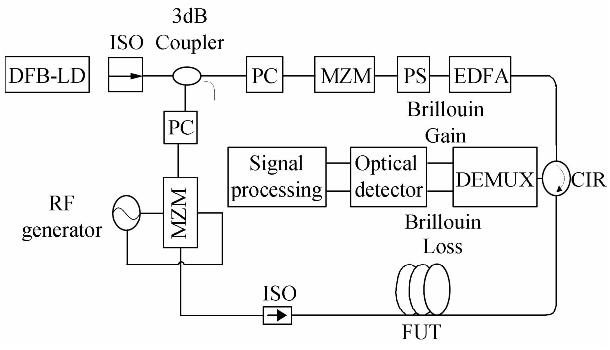


Fig. 1　Schematic diagram for BOTDA simulation (ISO=isolator, PC=polarization controller, PS=polarization Cscrambler, IR=circulator, MZM=Mach-Zehnder modulator)

$$\begin{aligned} E_{\mathrm{OCS}}(t) &= E(t)\mathrm{e}^{\mathrm{j}\omega_{\mathrm{c}}t}[\exp \mathrm{j}(m_{\mathrm{h}}\cos \omega_{\mathrm{m}}t)-\mathrm{j}\exp \mathrm{j}(-m_{\mathrm{h}} \cdot \\ &\sin \omega_{\mathrm{m}}t)] = E(t)\sum_{k-\infty}^{\infty} j^{k}[1-(-1)^{k}] * J_{k}(m_{\mathrm{h}}) \cdot \\ &\mathrm{e}^{\mathrm{j}(\omega_{\mathrm{c}}+k\omega_{\mathrm{m}})t} \approx E_{\mathrm{s}}(t)(\mathrm{e}^{\mathrm{j}(\omega_{\mathrm{c}}+\omega_{\mathrm{m}})t}+\mathrm{e}^{\mathrm{j}(\omega_{\mathrm{c}}-\omega_{\mathrm{m}})t}) \end{aligned} \tag{2}$$

where $E_{\mathrm{s}}(t)$ is the amplitude of the Stokes light. If the peak power associated with pump and Stokes light are relative low, the interaction (XPM, XGM and FWM) of the two side bands can be neglected. And the two side bands can be treated as two separated signal. So the equation[11] can be derived as

$$\begin{cases} \left(\dfrac{\partial}{\partial z}+\dfrac{n}{c}\dfrac{\partial}{\partial t}\right)E_{\mathrm{p}} = -Q_{\mathrm{D}}E_{\mathrm{sD}}-\dfrac{\alpha}{2}E_{\mathrm{p}} \\ \left(-\dfrac{\partial}{\partial z}+\dfrac{n}{c}\dfrac{\partial}{\partial t}\right)E_{\mathrm{sD}} = Q_{\mathrm{D}}^{*}E_{\mathrm{p}}-\dfrac{\alpha}{2}E_{\mathrm{sD}} \\ \left(\dfrac{\partial}{\partial t}+\Gamma\right)Q_{\mathrm{D}} = \dfrac{g_{\mathrm{B}}}{2}\Gamma_{1}E_{\mathrm{sD}}E_{\mathrm{p}} \end{cases} \tag{3}$$

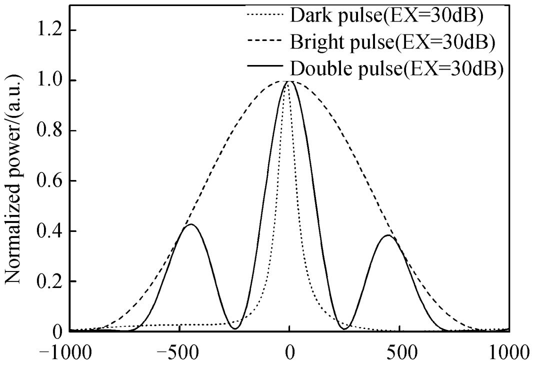
$$\begin{cases} \left(\dfrac{\partial}{\partial z}+\dfrac{n}{c}\dfrac{\partial}{\partial t}\right)E_{\mathrm{p}} = Q_{U}^{*}E_{\mathrm{sU}}-\dfrac{\alpha}{2}E_{\mathrm{p}} \\ \left(-\dfrac{\partial}{\partial z}+\dfrac{n}{c}\dfrac{\partial}{\partial t}\right)E_{\mathrm{sU}} = -Q_{\mathrm{U}}E_{\mathrm{p}}-\dfrac{\alpha}{2}E_{\mathrm{sU}} \\ \left(\dfrac{\partial}{\partial t}+\Gamma\right)Q_{\mathrm{U}} = -\dfrac{g_{\mathrm{B}}}{2}\Gamma_{1}E_{\mathrm{sU}}E_{\mathrm{p}}^{*} \end{cases} \tag{4}$$

$E_{\mathrm{sD}}(t)$ and $E_{\mathrm{sU}}(t)$ represent the amplitude of the two side band signal, while n is the refractive index, c is the velocity of light in vacuum, and g_{B} is gain factor. Γ_1 is the damping time of the phonon field and $\Gamma_1=1/T_{\mathrm{B}}$ where T_{B} is the lifetime of the phonon. The detuning parameters are defined as $\Gamma_1=\omega_{\pi}-\omega_{\Sigma}-\Omega_{\mathrm{B}}$, in which ω_{π} and ω_{Σ} indicate the angle frequency of the pump and Stokes light respectively[12-14]. Ω_{B} is the local Brillouin frequency of the fiber and $f(x, t)$ expresses the thermal noise in fiber which is the dominative factor for spontaneous Brillouin backscattering generation.

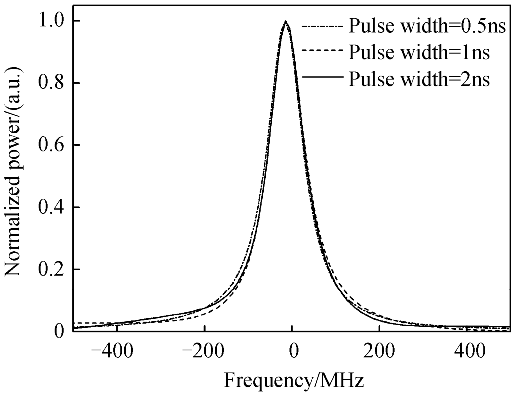
2　Simulations and analysis

A BOTDA operating at 1 550 nm was solved numerically with pump and stokes laser powers of 3 mW and 10mW respectively. And all the simulations presented here were performed with Brillouin parameters typical for the single-mode silica fibers: $\tau_{\mathrm{ph}}=10$ ns, $\nu_{\mathrm{B}}=12.8$ GHz, $g_{\mathrm{B}}=5\times 10^{-11}$ m/W, $A_{\mathrm{eff}}=50$ $\mu\mathrm{m}^2$, $v=0.2$ m/ns.

The measurements of simulated Brillouin spectrum of the strained section were presented along 10 m single mode fiber. Time-domain waveforms were calculated for a detuning frequency ranging from −5 000 to 5 000 MHz, with a 10 MHz step. As the Fig. 2 shows, the simulated Brillouin spectra of the strained section have been tested with 3 different pump pulse coding format pulses (conversional bright pulse, double-pulse and dark pulse) with pulse widths of 1ns whereas the rise/fall times were set to 0.1 ns. As the spectral heights vary over different orders of magnitude, the spectra have been normalized to allow comparison of the linewidth of BGS. As it is anticipated, with the same pulse width, the BGS of dark-pulse presents the narrowest linewidth which indicates the most precise frequency resolution. In the Fig. 2 (b), Brillouin spectra obtained by simulating dark pulses of 2, 1, and 0.5 ns are presented which have been also normalized to allow comparison of spectral widths. It will be observed that unlike the pulse width sensitive bright pulse pumped system, the spectral width of dark pulse pump system is essentially independent of pulse width.



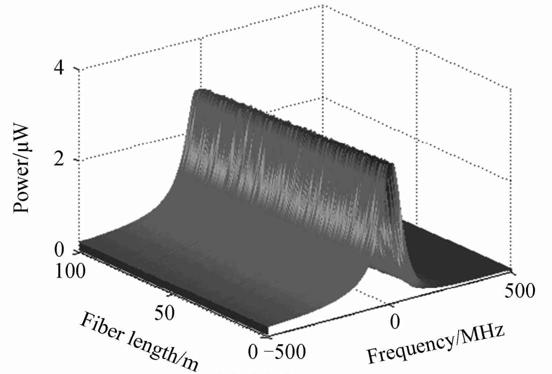
(a) Normalized Brillouin spectra using different pulse types with 1ns pulse width



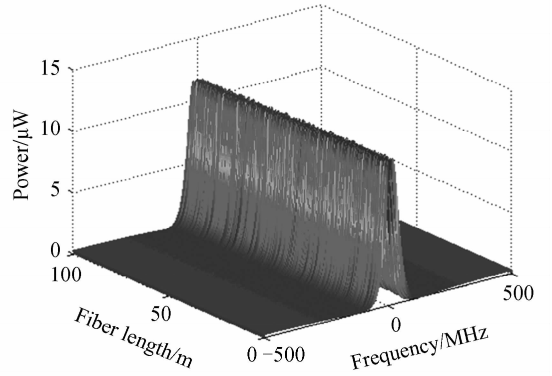
(b) Normalized dark-pulse spectrum calculated with different pulse widths

Fig. 2 Brillouin gain spectra with ER=30 dB

In order to evaluate the proposed DP-BOTDA, simulation tests were performed on a uniform 100 m long fiber with a 1 ns pulse width. The Stokes spectra were calculated for a frequency interval ranging from -500 to 500 MHz with a step of 1 MHz. The Stokes and the pump power used in the original DP-BOTDA were 1mw and 10 mW. The same power was used in the modified BOTDA, with a peak power of at each sideband. The Brillouin spectra of both the original and proposed DP-BOTDA were presented in Fig. 3. Influenced by the Quasi-CW component of the dark pulse pumping BOTDA, a slope of ~5 MHZ is introduced into the Brillouin spectrum. In our proposal, thanks to the counteraction between the Brillouin gain and loss signal, the influence of the Quasi-CW component was suppressed but the Brillouin spectra kept the Lorenz shapes.



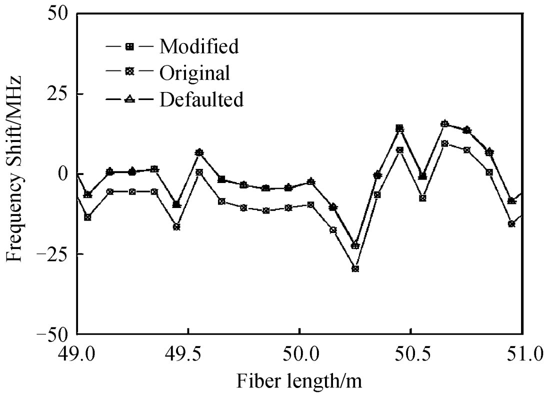
(a) Original type



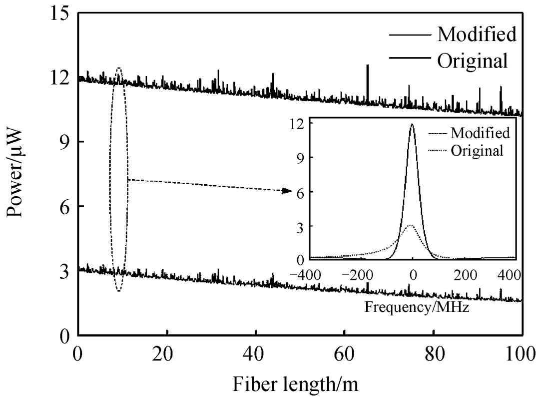
(b) Modified type

Fig. 3 The distribution of the Brillouin spectra of original and modified DP-BOTDA

A distribution of the frequency shift of along 2-m-long fiber from 49 m to 51 m was given in Fig. 4 (a) to analyze the frequency locating capability. In original DP-BOTDA, it can be clearly seen that affected by Quasi-CW component of the pump light, the frequency shift is at least 5 MHZ smaller than the defaulted ones which has been suppressed by subtraction of the Brillouin loss and gain signal in the modified DP-BOTDA. Fig. 4 (b) indicates that the power of the modified time domain signal is much larger than the original



(a) Along the 2-m-long fiber



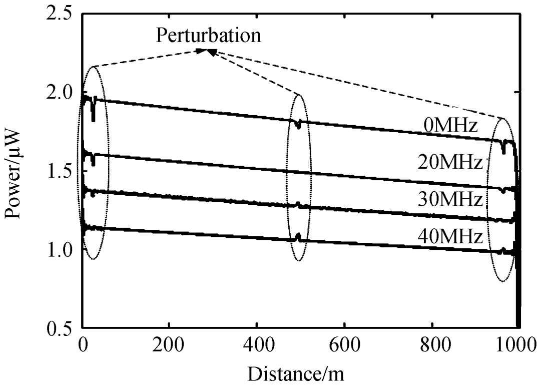
(b) Along 100-m-long fiber

Fig. 4 Frequency shift and power distribution of the DP-BOTDA and time domain signal

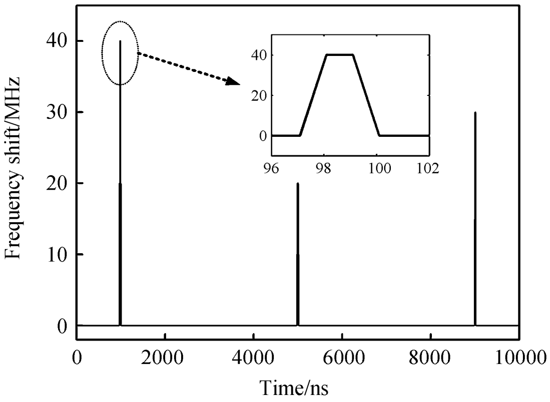
ones. And the fluctuation of the time domain signal indicates Brillouin frequency variation along the fiber.

In Fig. 4, Brillouin time domain signals are analyzed with 4 different detuning frequencies. Based on the principle described in section 2, 1 km single mode fiber is simulated. The fiber injected power of the pump light and the Stokes light are set as 20 mW ($L_{\rm eff}\approx 1$ km) and 6mw respectively with 1ns pulse width.

It is clearly indicated that this model can successfully locate the perturbation along the fiber. As the Fig. 5 (a) shows, 4 different detuning frequencies are detected in this simulation, corresponding to the perturbation frequencies along the fiber. Particularly, the amplitude of perturbation on the time domain indicates the accuracy of the model in describing the Brillouin frequency shift along the fiber. In frequency scanning method based BOTDA system, the location of a fiber under strain change can be determined by scanning the backscattering signal power. By detecting the signal power decreased or increased points. The Brillouin frequency shift distribution measured along the fiber is depicted in Fig. 5 (b). It can be observed that the measured curve coincided with the time domain signal curve. And the results confirmed that the dark pulse system enables us to measure distributed strain and temperature with a spatial resolution of 10 cm.



(a) The received Brillouin signal along the fiber



(b) The Brillouin frequency shift distribution

Fig. 5 The distribution of the time domain Brillouin signal and detected frequency shift

3 Conclusion

As a very probable method for high spatial resolution detection, the main limitation of DP-BOTDA is the total sensing length. To solving this problem, a simple BOTDA configuration is proposed in this paper to achieve much higher total sensing length. The simulations and discussion were conducted to demonstrate that by transferring the pump power to the sidebands, the influence of the CW component of the dark pulse pump signal is greatly suppressed and BGS with much narrower linewidth can also be generated. Simulation results show that 10 cm fiber frequency perturbation can be easily detected along beyond km-long single mode fiber. Besides in order to keep the BGS shape in this system, the intensity of the sidebands signal cannot be too large which in reverse limits the further sensing length increase.

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一种基于暗脉冲光布里渊时域分析仪的延长传感距离的方法

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摘　要：基于暗脉冲的布里渊时域分析仪系统中泵浦光和探测光的功率较高，相互作用强烈，严重限制了系统的有效传感距离。而现有的系统众多采用利用多段具有不同布里渊散射频率的光纤相互连接延长传感距离的方法，降低每段光纤上的受激布里渊散射效应，延长有效传感距离，但这种方案会增加的系统的复杂度，影响实际应用. 本文提出一种简单的暗脉冲光布里渊时域分析仪的结构，可在满足高空间分辨率的条件下，有效的延长系统的传感距离，取代通常的利用多段具有不同布里渊散射频率的光纤相互连接延长传感距离的方法. 利用基于光抑制载波的技术，产生具有两个边带的斯托克斯光. 斯托克斯光的两个边带和泵浦光相互作用，同时激发布里渊散射增益和衰减效应，在接收端利用两者接收信号的差，可抵消原有暗脉冲泵浦信号中准连续光对传感距离的影响，从而有效地延长系统的传感距离，并利用数值仿真的方法验证了此方法的有效性.

关键词：光时域分析仪；布里渊散射；暗脉冲；光纤传感