Optics Communications 367 (2016) 155–160

Contents lists available at ScienceDirect

Optics Communications

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

Optical pulse compression reflectometry based on single-sideband modulator driven by electrical frequency-modulated pulse

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ARTICLE INFO

Article history:
Received 22 December 2015
Received in revised form
12 January 2016
Accepted 13 January 2016
Available online 4 February 2016

Keywords:
Fiber optics sensors
Frequency modulation
Optical pulse compression reflectometry

ABSTRACT

We propose a novel scheme to generate a linear frequency-modulated optical pulse with high extinction ratio based on an electrical frequency-modulated pulse and optical single-sideband modulator. This scheme is proved to improve the stability and accuracy of optical pulse compression reflectometry (OPCR). In the experiment, a high spatial resolution of 10 cm and a long measurement range of 10.8 km using a laser source with 2-km coherence length are demonstrated.

1. Introduction

Optical fiber reflectometry is an important instrument to monitor intrinsic or external disturbance in optical fibers [1]. Different types of reflectometries have been proposed [2–5]. The first type of optical time domain reflectometry (OTDR) dates back to 1970s [2], which has been widely used for long-length interrogation although its spatial resolution was limited due to the required pulse energy and the intrinsic fiber attenuation. Another reflectometry, called optical frequency domain reflectometry (OFDR) [3], was developed to overcome such shortage since it is referred to the frequency modulation continuous wave (FWCW) radar technology. However, the measurement range of OFDR is physically limited by the half of coherence length of the laser source. In comparison, optical coherence domain reflectometry (OCDR) [4] and optical low coherence reflectometry (OLCR) [5] can also provide competitive spatial resolution but the measurement range is confined as well. Most recently, we proposed a new reflectometry inspired by pulse-compression radar [6], named pulse-compression OTDR [7] or optical pulse compression reflectometry (OPCR) [8], which can overwhelm the tradeoff between the spatial resolution and measurement range. An optical pulse with a long pulse duration and linear frequency modulation (LFM) is launched into an optical fiber and the backscattered light is coherently detected using matched filtering so as to significantly compress the original pulse duration. Consequently, OPCR is able to achieve a high spatial resolution and large signal to noise ratio, both of which are attributed to the wide LFM bandwidth.

In this work, we demonstrate a new-scheme OPCR by use of one optical single-sideband modulator (SSBM) and an electrically pulsed linear frequency modulation. Compared with the previous scheme based on two modulators [8], the new scheme can generate the electric pulsed LFM and optical LFM pulse with less complexity, broader bandwidth and larger extinction ratio. We successfully achieve 10 cm spatial resolution over 10.8 km measurement range although a laser source with coherence length of only 2 km is used.

2. Principle and experimental setup

Fig. 1 compares two schemes generating an optical LFM pulse for the OPCR with different extinction ratio. In both cases, an arbitrary waveform generator (AWG) is used to generate two synchronous electric waveforms of rectangular pulse and sawtooth. The period of the sawtooth is equal to the width of the rectangular pulse. In the original scheme [see Fig. 1(a)] [8], the sawtooth is connected with a voltage controlled oscillator (VCO) that drives a single sideband modulator (SSBM) to generate an LFM continuous light; the electric pulse is launched to a Mach–Zehnder modulator (MZM) so as to achieve an optical LFM pulse with finite (typically,

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http://dx.doi.org/10.1016/j.optcom.2016.01.034
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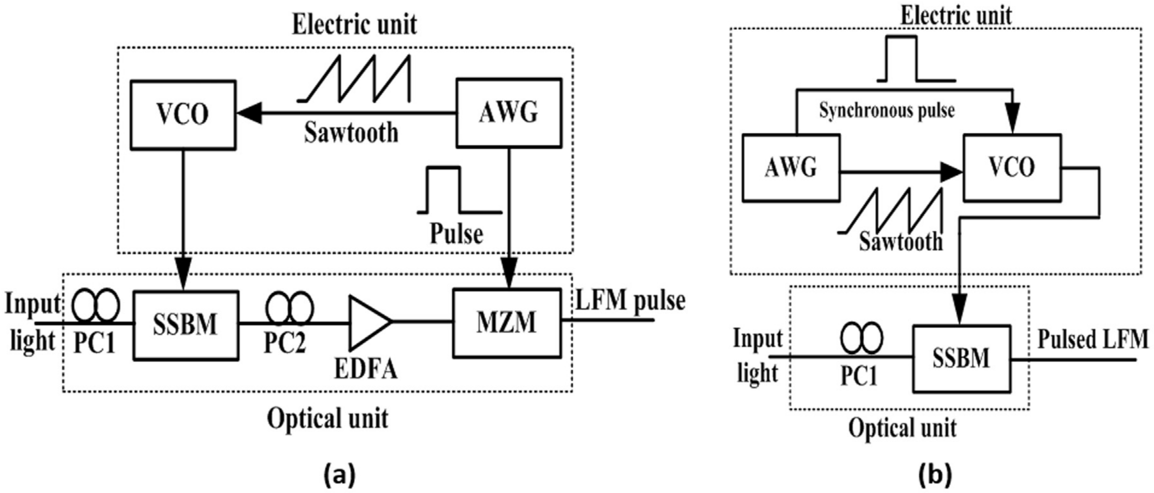

Fig. 1. Comparison of two different schemes to generate an optical LFM pulse. (a) The original scheme [8] and (b) the new scheme proposed in this work. VCO: voltage controlled oscillator; AWG: arbitrary waveform generator; SSBM: single-sideband modulator; MZM: Mach–Zehnder modulator; EDFA: erbium-doped fiber amplifier; PCs: polarization controllers.

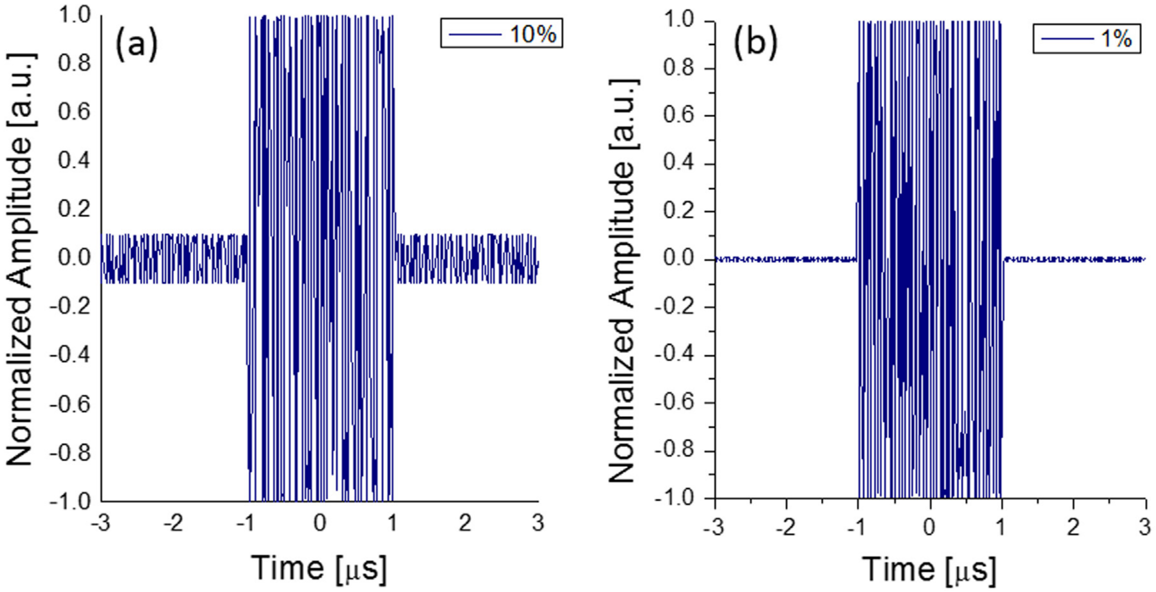

Fig. 2. Schematic comparison of the LFM pulse with different power extinction ratio. (a) $\eta=0.1$ and (b) $\eta=0.01$.

~20 dB) and unstable extinction ratio. As shown in Fig. 1(b), both electric waveforms in the new scheme are connected simultaneously with the VCO so as to generate an electrically pulsed LFM. The VCO drives the SSBM to generate an optical LFM pulse. As long as the rectangular pulse served as supply voltage switches from high-level voltage to zero voltage, the VCO changes from normal status (high voltage, V_1) to shut-down status (almost zero voltage, V_0), generating an electrically pulsed LFM with high extinction ratio. Correspondingly, an optical LFM pulse is formed with greater extinction ratio than that under the additional assistance of the MZM. Besides, the complexity of the new scheme is significantly reduced. In the new scheme, only one SSBM and one polarization controller (PC) are sufficient to generate the optical LMF pulse. However, in [8], except for this, one more MZM, PC, and erbium-doped fiber amplifier (EDFA) are required.

The electric field of SSBM is given by [10]

$$E(t) \propto J_0(m)e^{i\omega_0 t} + J_1(m)e^{i(\omega_0-\omega_{RF})t}, \tag{1}$$

where m is the modulation depth that is proportional to the driven voltage (i.e. V_{VCO}), ω_0 is the optical angular frequency, ω_{RF} is the electric angular frequency, and $J_{0,1}(m)$ denotes the Bessel functions corresponding to the magnitudes of optical carrier and single sideband. The extinction ratio of the SSBM is determined by

$$ER_{SSB} \equiv 10{*}\log 10\frac{J_1(m_1)^2}{J_1(m_0)^2} \approx ER_{VCO}, \tag{2}$$

where m_1 (m_0) corresponds to the modulation depth when the VCO is high (lower) voltage of V_1 (V_0), $ER_{VCO}=20\log(V_1/V_0)$ denotes the power extinction ratio of the VCO, and the approximation is valid for low-depth modulation (the case in this study).

The backscattered curve in the OPCR is expressed by [8]

$$y(t) = A(t){*}C(t), \tag{3}$$

where $A(t)$ determines the backscattered light attributed to Rayleigh scatter occurring anywhere in the fiber, splicing loss at particular points, and end reflection due to Fresnel reflection. $C(t)$ stands for the impulse response (i.e. pulse compression) of the electrically pulsed LFM given by