Optical Fiber Technology 19 (2013) 574–578

Contents lists available at ScienceDirect

Optical Fiber Technology

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Simulation analysis of an improved optical triangular-shaped pulse train generator based on quadrupling RF modulation incorporating fiber dispersion-induced power fading

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ARTICLE INFO

Article history:
Received 13 June 2013
Revised 22 August 2013
Available online 14 October 2013

Keywords:
Microwave photonic
Triangular-shaped pulse train
Quadrupling RF modulation
Fiber dispersion-induced power fading

ABSTRACT

We report an improved approach to generate optical triangular-shaped pulse train using quadrupling RF modulation and fiber dispersion-induced power fading. In the proposal, quadrupling RF modulation (via a dual-parallel Mach–Zehnder modulator) is employed to generate four primary optical sidebands (±2nd and ±6th) in spectrum. Then a piece of single mode fiber is connected as the dispersive media. Because of the power degradation induced by fiber dispersion, the undesired 8th order harmonic in optical intensity can be removed. It is found that when the modulation index is adjusted to a proper value ($m = 4.438$), optical intensity with its expression corresponding to the Fourier expansion of idea triangular-shaped waveform can be found. Since the quadrupling RF modulation technique is employed, repetition rate of the target pulse train is four times of the driving frequency, which makes pulse train generation with higher repetition rate or smaller pulse duration possible.

1. Introduction

All-optical processing and manipulation is considered as the key issue in all-optical network. According to recent researches, optical triangular-shaped pulses can be used as the pump source in all-optical conversion, pulse compression and signal copying [1–4]. For example, combined with the cross-phase-modulation (XPM), optical pulses with triangular shape can be used for all-optical conversion of time-division multiplexed to wavelength multiplexed signals [2]. It was demonstrated in Ref. [3] that optical triangular-shaped pulses can lead to better than twofold performance improvement of wavelength-conversion by using self-phase modulation (SPM) in fiber and offset-filtering. In Ref. [4], a technique of copying optical pulses in both frequency and time domain and subsequent propagation in a dispersive medium was proposed and demonstrated using optical triangular-shaped pulses pump. Recently, lots of techniques have been proposed to generate optical triangular-shaped pulses [5–11]. One popular approach uses a mode-lock laser (MLL) as the source. For instance, in Ref. [5], Boscolo et al. propose a prototype of triangular-shaped pulses generator using pulse pre-chirping combined with a single normally dispersive fiber. In Ref. [6], triangular pulse generation in fiber lasers have been analyzed by Boscolo et al. Then in Ref. [7], Ye et al. propose a triangular-shape shaping module using two polarization controller and a piece of polarization-maintain fiber. In Ref. [8], optical pulse shaping method based on temporal coherent synthesization is proposed to generate triangular-shaped pulses. Since the above prototype all use a MLL (or ultrashort pulse laser) as the source, the generated pulses' repetition rate is highly dependent on the laser source. As to the application in Ref. [2], pulse train with tunable repetition rate seems to be a better choice. There is another approach using a single continuous-wave (CW) laser as the source. In the prototype, external RF modulation is employed, which makes continuous repetition rate tuning possible. For instance, in Ref. [9,10], Dai et al. report and analyze a versatile waveform generator based on comb generation. Using this technique, optical triangular-shaped pulses with tunable repetition rate can be generated. Later in Ref. [11], optical carrier-suppression modulation incorporating fiber dispersion has been proposed to generate triangular-shaped pulse train. The primary principle is to make the expression of optical intensity approximately equal to the Fourier expansion of idea triangular-shaped waveform. It is found that the pulse repetition rate is twice of the driving frequency.

In this work, a further improved approach for triangular-shaped pulse train generation is proposed and analyzed, by theory and simulation. In the prototype, a dual-parallel Mach–Zehnder modulator (DP-MZM) is employed to replace the original dual-drive Mach–Zehnder modulator (DD-MZM) in Ref. [11]. One typical

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http://dx.doi.org/10.1016/j.yofte.2013.09.006

DP-MZM can be considered as two single-drive sub-MZMs (MZ-a and MZ-b) embedded in a main-MZM (MZ-c). With appropriate bias control, the DP-MZM can operate at quadrupling RF modulation. Thus four primary optical sidebands (±2nd and ±6th) can be obtained in optical spectrum. Then, by using the dispersion induced power fading in a piece of single mode fiber (SMF), the undesired 8th order harmonic can be removed. This work is first analyzed by theory and then verified by simulation. It is found that with carefully adjustment of the modulation index ($m = 4.438$), the expression of optical intensity will approximately equal to the Fourier expansion of idea triangular-shaped waveform. Differ from the research in Ref. [11], this work is based on quadrupling RF modulation technique, thus the repetition rate is four time of the driving frequency, which makes this work a further improved approach when compared to Ref. [11].

2. Theory

The schematic setup is shown in Fig. 1. A lightwave from a continuous-wave (CW) laser is sent to a dual-parallel Mach–Zehnder modulator (DP-MZM). A RF signal is firstly split by a 90° hybrid coupler and then applied to two sub-MZMs (MZ-a and MZ-b) of the DP-MZM. Because of the x-cut design, MZ-a and MZ-b are configured for the push–pull operation, and each has independent DC bias. It is assumed that these two sub-MZMs are identical. To obtain the quadrupling RF modulation, three bias voltages of DP-MZM should be properly adjusted. Here, MZ-a, MZ-b and MZ-c should be biased at MATP, MATP and MITP, respectively, where MATP and MITP denote the maximum and minimum transmission point of modulator.

The mechanism of quadrupling RF modulation is given as follows. Considering an RF signal with $V_{RF}cos(\omega_{RF}t)$, at a frequency of $\omega_{RF}/2\pi$ and an amplitude of V_{RF}, driving the DP-MZM, the output signal of modulator (point A in Fig. 1) can be expressed as (extinction ratio of DP-MZM is assumed to be infinite $\varepsilon_r = \infty$)

$$\begin{aligned} E_A(t) &= \frac{E_{in}(t)}{2}\left\{\exp\left[j\frac{V_{RF}}{2V_\pi}\cos(\omega_{RF}t)\right] + \exp\left[-j\frac{V_{RF}}{2V_\pi}\cos(\omega_{RF}t)\right]\right. \\ &\quad \left. - \exp\left[-j\frac{V_{RF}}{2V_\pi}\sin(\omega_{RF}t)\right] - \exp\left[+j\frac{V_{RF}}{2V_\pi}\sin(\omega_{RF}t)\right]\right\} \\ &= \frac{E_{in}(t)}{2}\sum_{k=-\infty}^{\infty} a_{4k-2}\exp[j(4k-2)\omega_{RF}t] \end{aligned} \tag{1}$$

where $a_{4k-2} = \left[j^{4k-2} + j^{4k-2}(-1)^{4k-2} - (-1)^{4k-2} - 1\right]J_{4k-2}(m)$ (2)

and $E_{in}(t) = E_0\exp(j\omega_0 t)$ represents the optical field from the CW laser, where E_0 and ω_0 denote its amplitude and angular frequency. The parameter $m = \pi V_{RF}/2V_\pi$ is defined as the modulation index, where V_π is the half-wave switching voltage of DP-MZM.

Fig. 2 shows the Bessel function of the first kind of order 4k−2, $J_{4k-2}(m)$ versus modulation index, m. Note that $J_2(m) \approx 3J_6(m)$ can be obtained when modulation index is properly adjusted to $m = 4.438$. In practice, by employing a DP-MZM with a low half-wave switching voltage, such a high modulation index ($m = 4.438$ in our case) is possible. Also note that the impact of 10th order harmonic is negligible small. Thus $E_A(t)$ can be simplified as

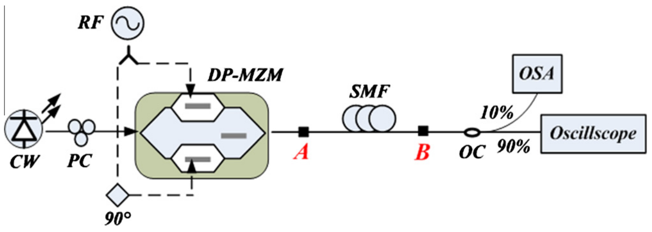

Fig. 1. Schematic setup of the proposed generator (CW, continuous-wave laser; DP-MZM, dual-parallel Mach–Zehnder modulator; PC, polarization control; SMF, single mode fiber; OC, optical coupler; OSA, optical spectrum analyzer).

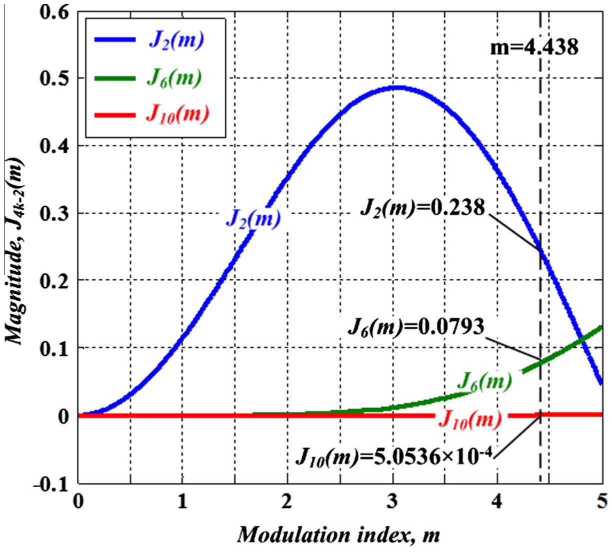

Fig. 2. Bessel function of the first kind of order 4k − 2, $J_{4k-2}(m)$ versus modulation index, m.

$$\begin{aligned} E_A(t) \propto{}& [a_{-6}\exp(-j6\omega_{RF}t) + a_{-2}\exp(-j2\omega_{RF}t) + a_2\exp(j2\omega_{RF}t) \\ &+ a_6\exp(j6\omega_{RF}t)] \end{aligned} \tag{3}$$

The corresponding intensity of $E_A(t)$ is

$$\begin{aligned} I_A(t) \propto{}& \{[a_{-6}^2 + a_{-2}^2 + a_2^2 + a_6^2] \\ &+ 2(a_{-2}a_2 + a_{-6}a_{-2} + a_{-2}a_{-6})\cos(4\omega_{RF}t) \\ &+ 2(a_{-6}a_2 + a_{-2}a_6)\cos(8\omega_{RF}t) + 2a_{-6}a_6\cos(12\omega_{RF}t)\} \end{aligned} \tag{4}$$

As expressed in Eq. (4), there are three RF components (4th, 8th and 12th order harmonic) in the optical intensity. To removed the undesired 8th order harmonic ($\cos(8\omega_{RF}t)$, a piece of SMF is employed. Considering the transmission function of the SMF [12], the optical field and its corresponding intensity at the output of SMF (point B in Fig. 1) can be concluded as

$$\begin{aligned} E_B(t) \propto{}& \left[a_{-6}\exp\left(-j6\omega_{RF}t + j18\beta_2 L\omega_{RF}^2\right)\right. \\ &+ a_{-2}\exp\left(-j2\omega_{RF}t + j2\beta_2 L\omega_{RF}^2\right) \\ &+ a_2\exp\left(j2\omega_{RF}t + j2\beta_2 L\omega_{RF}^2\right) \\ &\left.+ a_6\exp\left(j6\omega_{RF}t + j18\beta_2 L\omega_{RF}^2\right)\right] \end{aligned} \tag{5}$$

$$\begin{aligned} \text{and } I_B(t) \propto{}& \left\{\left[a_{-6}^2 + a_{-2}^2 + a_2^2 + a_6^2\right] + 2a_{-2}a_2\cos(4\omega_{RF}t)\right. \\ &+ 2a_{-6}a_6\cos(12\omega_{RF}t) \\ &\left.+ 4a_6a_2\cos\left(16\beta_2 L\omega_{RF}^2\right)\cos(8\omega_{RF}t)\right\} \end{aligned} \tag{6}$$

where $\beta_2 = -\lambda_0^2 D/(2\pi c)$, λ_0—optical central wavelength, c—speed of light in vacuum, L—fiber length and D—dispersion parameter. By adjusting the fiber dispersion $\beta_2 L$ in Eq. (6), $\cos(8\omega_{RF}t)$ can be fully removed. In that case, the following condition is satisfied:

$$\beta_2 L = -\left(\frac{2n+1}{2}\right)\frac{\pi}{16\omega_{RF}^2}, \quad n = 0, 1, 2, \ldots \tag{7}$$

Substituting Eqs. (2) and (7) into Eq. (6), the output optical intensity becomes

$$I_{out}(t) \propto \cos(4\omega_{RF}t) + \frac{J_6^2(m)}{J_2^2(m)}\cos(12\omega_{RF}t) \tag{8}$$