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Microwave generation analysis with higher order dispersion parameters in two cascaded Mach-Zehnder modulators

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ABSTRACT

Dispersion is one of the major limiting factors for microwave/millimeter wave generation in microwave photonics. In this paper, we analyze the individual and combined effect of second order-, third order-, fourth order and fifth order dispersion parameter on microwave/millimeter wave generation. We have used the two cascaded Mach-Zehnder modulators in our proposed model, which have been not discussed earlier. Intensity at the output of photodetector versus modulation depth (β) with effects of dispersion parameters have been discussed and it has been found that output intensity of photodetector reduces when dispersion term up to fifth order are added.

1. Introduction

Microwave photonics (MWP) is the study of devices at microwave frequency and their application to the optical devices [1–3]. Research in the field of microwave photonics is going on in a rapid phase. Various application of MWP includes like radar, communication system, sensor network, warfare systems [4]. Main advantages of MWP technology over conventional electrical-transmission technology include reduced size, weight and cost, low and constant attenuation over the entire microwave and millimeter-wave modulation frequency range, immunity to electromagnetic interference, low dispersion, no electro-optical conversions and high data-transfer capacity [5]. In the past few months various methods have been proposed for microwave/millimeter signal generation but simple method is beating of optical carriers from two laser sources at THz frequency, followed by photodiode (PD) [6,7]. But its disadvantage is that high phase noise is produce if phase of two beating optical carriers are not correlated [6]. Other advance methods include optical injection locking [8,9] and optical phase – locked loop (OPLL) [10,11]. But problem with this method is that optical sources with very narrow linewidth mainly in KHz are required [12]. Solution to this problem is that we can use Lithium-niobate Mach-Zehnder modulator ($LiNbO_3$-*MZM*), which involves concept of frequency multiplication [6]. O'Reilly et al. proposed a method to generate microwave/millimeter wave using MZM [13]. Mach-Zehnder modulator (MZM) can be operated in two transmission points: maximum transmission point (MAXTP) and minimum transmission point (MINTP) [14].

Dispersion is one of the most important limiting factors in MWP. Dispersion is spreading out of light pulses as they travel along a fiber and mainly occur due to the dependence of speed of light through the fiber on the wavelength [6]. Unlike attenuation, dispersion does not weak a signal. It only blurs the optical signal transmitted through optical fiber. In this paper, we analyze the effect of higher order dispersion term, i.e. up to fifth order, dispersion parameters on microwave/millimeter wave generation using two cascaded MZMs.

Section 2 consists of the theory of proposed model for millimeter wave/microwave generation, followed by the derivation of output of two MZM in series with higher order dispersion terms. In Section 3 we plotted various graphs of output intensity of photo detector versus modulation depth (β) considering individual dispersion term and combinations of dispersion term up to fifth order.

2. Proposed model

A novel approach to generate microwave/millimeter wave using two series MZMs is shown in Fig. 1. An optical carrier of 193.1 THz and an electrical drive signal of frequency 12.5 GHz is applied to an first Mach-Zehnder modulator (MZM). We have used ITU's G.655 fiber of different length for calculation and simulation.

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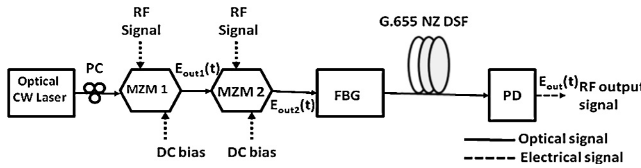

Fig. 1. Generalized diagram of millimeter wave/microwave frequency generation system using two series MZMs. CW: continuous wave, PC: polarization controller, MZM: Mach-Zehnder modulator, FBG: Fiber Bragg Grating, G.655 NZ DSF: International Telecommunication Union's standardized Non Zero Dispersion Shifted Fiber, PD: photo detector.

Consider the case when only one arm of first MZM is modulated, the phase difference become [6]:

$$\Delta\phi = \frac{\Delta n \cdot 2\pi \cdot L}{\lambda} \tag{1}$$

where Δn is the optical refractive index change in the arm of modulator, λ is optical wavelength, L is the modulation depth. Due to pockel effect in $LiNbO_3$ MZM, Eq. (1) become [6]:

$$\Delta\phi = \frac{n_0^3 \cdot r_{ij} \cdot V_{RF} \cdot 2\pi \cdot L}{2 \cdot d \cdot \lambda}$$

where r_{ij} is the electro-optic coefficient of $LiNbO_3$ crystal, V_{RF} is the amplitude of applied low frequency RF signal, d is the distance between MZM arms.

As $V_\pi = d \cdot \lambda / n_0^3 \cdot r_{ij} \cdot L$, therefore above equation reduces to $\Delta\phi = V_{RF} \cdot \pi / V_\pi$ where V_π is the voltage value at which voltage induced phase difference reaches 180°.

If the MZM is driven by a low frequency electrical signal and biased with a constant DC voltage then phase difference become [6]:

$$\Delta\phi[V(t)] = \phi_0 + \frac{V_{RF} \cdot \pi}{V_\pi} \tag{2}$$

where $\Delta\phi[V(t)]$ is the optical phase difference caused by between the two arms of the MZM, ϕ is a constant phase shift, E_{RF} is the amplitude of the electrical drive signal. If the MZM is driven by a sinusoidal electrical signal and biased with a constant dc voltage, $\phi[V(t)]$, then electric field at the output of a lithium niobate MZM, i.e., [6] $E_{out1}(t) = E_0(t) \cdot \cos\left[\frac{\phi[V(t)]}{2}\right] \cdot \cos(\omega_0 t)$, can be approximately expressed by: $E_{out1}(t) = E_{in}(t) \cdot \cos\left[\frac{\phi[V(t)]}{2}\right]$

or

$$E_{out1}(t) = E_0(t) \cdot \cos\left[\frac{\phi\,[V(t)]}{2}\right] \cdot \cos(\omega_0 t) \tag{3}$$

where $E_0(t)$ and ω_0 are, respectively, the electric field amplitude and the angular frequency of the input optical carrier, $V(t)$ is the applied RF electrical drive voltage. The generalized electric field equation at the output of modulator up to n terms can be written using Eq. (3) and Eq. (4), as follows [14]:

$$\begin{aligned} E(t) &= E_0 \cos\left(\Phi/2\right)\left\{\cos\left(\omega_0 t + \Phi/2\right) J_0\left(\beta\right) + \right. \\ &\sum_{n=1}^{\infty}(-1)^n J_{2n}\left(\beta\right)\left[\cos\left(\omega_0 t + 2n(\omega_{RF} t + \phi) + \Phi/2\right) + \cos\left(\omega_0 t - 2n\left(\omega_{RF} t + \phi\right) + \Phi/2\right)\right]\Big\} \\ &+ E_0 \sin\left(\Phi/2\right)\left\{\sum_{n=1}^{\infty}(-1)^n J_{2n-1}\left(\beta\right)\left[\cos(\omega_0 t + (2n-1)(\omega_{RF} t + \phi)(+\Phi/2) + \cos(\omega_0 t - (2n-1)(\omega_{RF} t + \phi) + \Phi/2)\right]\right\} \end{aligned} \tag{4}$$

where $\beta = (V_{RF}/V_\pi) \cdot (\pi/2)$ is a modulation depth, Φ is the Phase difference between the arms of the modulator and ϕ is the phase of the electrical drive signal. The MZM can be operated at either Maximum transmission point (MAXTP), i.e. $\Phi = 0$ or Minimum transmission point (MINTP), i.e. $\Phi = \pi$, [14]. Hence, by connecting two MZMs in series we get four combinations: (1) MAXTP, MAXTP; (2) MAXTP, MINTP; (3) MINTP, MAXTP; (4) MINTP, MINTP. An FBG (Fiber Bragg Grating) is connected at the output of the MZM to remove the optical carrier and hence act as optical filter.

2.1. MAXTP, MAXTP

As both MZMs are operating at MAXTP. Therefore, $\Phi = 0$ for both MZMs. Expanding Eq. (4) for $n = 2$, the electric field ($E_{out1}(t)$) at the output of first MZM is given by:

$$E_{out1}(t) = E_0\left\{J_0(\beta_1).\cos(\omega_0 t) - J_2(\beta_1)\cos(\omega_0 t - 2\omega_{RF} t - 2\phi_1) - J_2(\beta_1)\cos(\omega_0 t + 2\omega_{RF} t + 2\phi_1)\right\} \tag{5}$$

where ϕ_1 is the initial phase of an electrical drive signal for MZM1 and β_1 is the modulation depth of MZM1. If the attenuation of the Fiber Bragg Grating at its center notch wavelength is α *dB*. The electric field at the output of FBG becomes:

$$E_{out1}(t) = E_0\left\{kJ_0(\beta_1).\cos(\omega_0 t) - J_2(\beta_1)\cos(\omega_0 t - 2\omega_{RF} t - 2\phi_1) - J_2(\beta_1)\cos(\omega_0 t + 2\omega_{RF} t + 2\phi_1)\right\} \tag{6}$$

where k is the electrical field attenuation factor and related to α by $\alpha = -20\,log_{10}\,k$.