Energy efficient photonic millimeter-wave generation using cascaded polarization modulators

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***Abstract*— A filter-less millimeter-wave generation scheme consisting of four polarization modulators in series, each followed by a polarizer is proposed to achieve optoelectronic frequency octupling. Theoretical analysis of the architecture is done by a transfer function method, validated by industry-standard software simulation. The circuit shows high potential in achieving desired performance with lower input RF power when compared to the another configuration. Effects of imbalances in the key circuit parameters are also investigated.**

I. Introduction

One of the key aspects of the radio-over-fiber (ROF) technology to meet the demand of future broadband wireless access is efficient and cost-effective schemes for the generation and transmission of millimeter-wave signal. Several techniques are proposed for the generation of optical millimeter-wave, among them frequency multiplication based on external modulation is proven to have higher spectral purity, simplicity and stability. Frequency doubling [1], quadrupling [2], sextupling [3], octupling [4]–[7] techniques are demonstrated. In [3], a generalized cascaded architecture is proposed to achieve greater RF power efficiency over functionally equivalent parallel structure [8]. Frequency octupling with a wide range of operating modulation range is achieved [4]–[5]. Due to the DC bias drift and unbalanced splitting ratio intrinsic to the Mach-Zehnder modulator (MZM), the practical applications become limited. Hence recently, polarization modulator based optical millimeter wave generation has attracted greater attention of researchers due to its bias-free operation and high extinction ratio.

In this report, a single arm architecture consisting of 4 polarization modulators (PolM) in series, each followed by a polarizer (Pol) is proposed as an optoelectronic method of microwave frequency octupling. The optical carrier and all sidebands except the odd integer multiples of 4th harmonics are suppressed without the necessity of any optical or electrical filter or careful adjustment of RF drive voltage. The circuit can operate at very low input RF power. Different non-ideal factors are taken into consideration to evaluate the overall performance on the basis of electrical side harmonic suppression ratio (ESHSR).

II. Operation Principle

The single stage cascaded PolM configuration proposed for the frequency octupling is shown in Fig. 1. The key element is the intensity modulator consists of a polarization modulator followed by a polarizer. The alignment of the polarizer angle and the state of the polarization of the input light relative to the principle axis of the respective PolM determine the biasing condition of the intensity modulator.

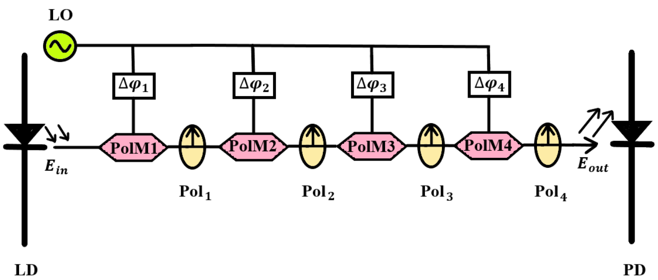

Fig. 1. Schematic diagram of the proposed frequency octupling architecture. LD: laser diode; PD: photo-diode; LO: local oscillator.

The optical field at the input of the cascaded structure is defined as

$$E_{in}(t) = E_{in}\exp(i\omega_c t) \qquad (1)$$

where E_{in} is the peak amplitude and ω_c is the angular frequency of the optical carrier.

Consider all the polarization modulators with principal axes aligned with the x and y direction. The amplitude transmission function of the intensity modulator can be given by

$$T_n = \cos(\O_n - \Theta_n)\cos[\{(\pi V_{RF})/V_\pi\}\cos(\omega_{RF}t+\Delta\varphi_n)] + i\cos(\O_n+\Theta_n)\sin[\{(\pi V_{RF})/V_\pi\}\cos(\omega_{RF}t+\Delta\varphi_n)] \qquad (2)$$

where $\O_n$ is the polarizer angle, Θ_n is the polarization state of the light wave input to the PolM$_n$, V_{RF} is the peak RF drive amplitude, ω_{RF} is the RF angular frequency and $\Delta\varphi_n$ is the phase shift of nth RF drive introduced to the nth polarization modulator. To bias each intensity modulator at its minimum transmission point (MITP), the polarizer angles are chosen to be $\O_n = \pm 45^0$ while Θ_n is of opposite polarity with same magnitude. The transfer function of each intensity modulator can be expressed as

$$T_n = i\sin[m\cos(\omega_{RF}t+\Delta\varphi_n)] \qquad (3)$$

where $m = (\pi V_{RF})/V_\pi$. Taking $\Delta\varphi_n = (n\pi)/4$ (n=0, 1, 2, 3) and utilizing the Jacobi-Anger expansion, the output optical field can be expressed as

$$E_{out} = E_{in}[\{J_4(r_+m)+J_4(r_-m)\}\sin(4\omega_{RF}t) - \{J_{12}(r_+m)+J_{12}(r_-m)\}\sin(12\omega_{RF}t) + \{J_{20}(r_+m)+J_{20}(r_-m)\}\sin(20\omega_{RF}t)\ldots.] \qquad (4)$$

where J_n is the Bessel function of the first kind of order n, $r_+=(2.828)\cos(\pi/8)$ and $r_-=2.828\sin(\pi/8)$. It can be seen from (4) and fig. 2 that all the sidebands alongside the optical carrier in the Jacobi-Anger expansion are suppressed except the odd multiples of 4th harmonic. The effects of the unsuppressed higher-order harmonics can be neglected for $m<\pi$. Frequency octupling can be achieved by this circuit

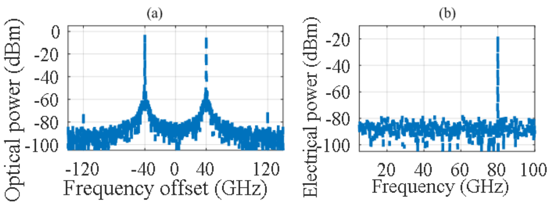

Fig. 1. (a) Optical spectrum and (b) electrical spectrum of the frequency 8-tupling signal

after passing the output onto a photodiode.

III. Simulation and Results

The proposed system is simulated using the Virtual Photonics Inc. (VPI) software package. A continuous wave distributed feedback (DFB) laser at a wavelength of 1550 nm with average power of 10 mW is used as the optical input. Four PolMs with their principal axes aligned with the x and y direction are cascaded. The half wave voltage of each PolM is taken as 1V. The input light is linearly polarized at 45^0. To bias the PolM-polarizer intensity modulators at the minimum transmission point (MITP), polarizer angles are selected accordingly (i.e. -45^0 for Pol_1, Pol_3 and $+45^0$ for Pol_2 and Pol_4 respectively). A 10 GHz sinusoidal RF drive signal having amplitude of 0.67 V is applied with appropriate RF phase relation (i.e. 0^0, 45^0, 90^0 and 135^0 for $PolM_1$, $PolM_2$, $PolM_3$ and $PolM_4$ respectively). A PIN diode with a responsivity of 0.8 A/W is used for detecting the output signal.

Fig. 2 shows the optical and electrical spectra at the output of the configuration. As shown in fig. 1(a), the optical carrier and all the sidebands except the odd multiple of 4^{th} order are effectively suppressed. The power of the two 4^{th} order harmonics is 66.9 dB higher than that of the other pronounced unwanted harmonics. After beating at the photodetector, a pristine frequency component at 80 GHz is obtained as shown in fig. 1(b).

Fig. 3 shows the comparison based on the RF power efficiency of the proposed architecture and another functionally equivalent 8-tupling architecture consisting of 4 parallel MZMs biased at the maximum transmission point (MATP). The setups have similar setting with the same half-wave voltage for each modulator. The x axis of the plot shows the applied RF input power to each modulator in dBm, while the y axis depicts the generated RF power for a load resistance of 50Ω. It can be observed that for the same output power, the proposed circuit needs ~6 dB less in input RF power than the parallel architecture. The operating range of the proposed architecture becomes small compared to the other but it can be used for a range of input RF power as low as 4 dBm to achieve output power greater than -23 dBm with ESHSR > 55 dB.

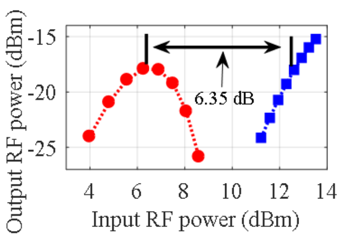

Fig. 2. Comparison between the proposed structure and two functionally equivalent parallel structures.

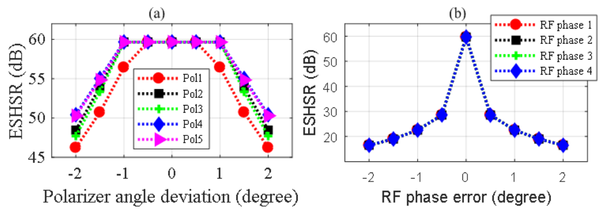

Fig. 4. ESHSR variation due to the drift of (a) polarizer angle and (b)RF drive phase from ideal condition

Drifts from the ideal condition are also investigated. Fig. 4 shows the variation of ESHSR due to the deviation in polarization angle and RF drive phase from their ideal condition. It can be observed from Fig. 4(a) that the first polarizer in the cascaded structure has the most pronounced effect on the performance, but still operation with ESHSR greater than 40 dB can be achieved with $\pm 2^0$ drift in any polarizer angle. ESHSR dependence on RF drive phase is more severe. Fig. 4(b) shows an almost identical performance degradation for individual RF drive phase deviation. Careful RF phase maintenance can limit the phase drift into $\pm 1^0$ to achieve ESHSR greater than 20 dB.

IV. Conclusion

In summary, a photonic circuit architecture is proposed as an energy efficient method to perform frequency octupling. The circuit can operate at lower RF drive level with ~6 dB RF advantage compared to functionally equivalent circuit. Moreover, the circuit requires no DC bias, optical filtering and careful adjustment of RF drive level for sideband suppression. Effects of imbalances of the various circuit parameters are also investigated.

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