Optical frequency multiplication technique using cascaded modulator to achieve RF power advantage

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***Abstract*— An optical millimeter-wave generation scheme consisting of four Mach-Zehnder modulator in series, each biased at its maximum transmission point is analysed by an optical path tracing method. Simulation using Virtual Photonic Inc. software package is presented as a proof of concept. The simulation results show that the proposed architecture can perform frequency octupling function with a significant RF advantage. The suppression of carrier and other unwanted harmonics by design, lower RF input power, wide operating range in terms of modulation index with satisfactory performance, and a simple filterless architecture make this circuit an attractive choice to be integrated in any material platform that offers electro-optic modulators.**

I. Introduction

The demand of high capacity wireless communication networks to deliver multi-Gb/s services and to support ever growing data traffic can be met by the usage of a suitable broadband frequency spectrum. Congested lower frequency bands and complicated electronic millimeter-wave (mm-wave) generation suggests frequency multiplication techniques based on external modulation in optical domain to be an attractive choice to access mm-wave band. Various multiplication factors have been achieved employing Mach-Zehnder modulator (MZM) [1-2], polarization modulator [3], Sagnac loop [4] etc. In [2], the generation of V-band 60 GHz and W-band 80 GHz mm-wave signals utilizing frequency octupling is experimentally demonstrated. A generalized architecture is proposed for any multiplication factor which shows greater RF power efficiency over functionally equivalent parallel structure [5-6].

In this report, a cascaded configuration consisting of 4 MZMs, each biased at its minimum transmission point (MITP) is proposed as a superior optical millimeter-wave generation scheme. The functionality of frequency octupling is analyzed by an optical path tracing method. An optical path can be expressed as a phasor if the optical components are optically linear. The time variant nature of active elements can be handled by a focus on pure RF carriers and the Jacobi-Anger expansion. Satisfactory performance in terms of spectral purity, tunability and RF power efficiency is observed by simulation. Its simple architecture has the feasibility to be integrated in any material platform that offers electro-optic modulators.

II. Operation Principle

The proposed frequency octupling circuit utilizing cascaded MZM configuration is shown in Fig. 1(a). The series architecture can be modelled by its equivalent parallel architecture. There are 2^N paths through the structure corresponding to all choices of the upper and lower arms in

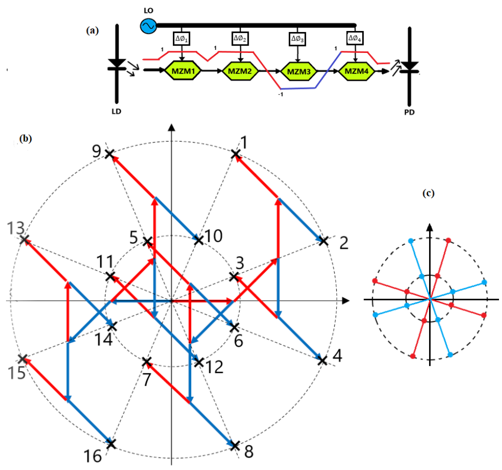

Fig. 1. (a) Schematic diagram of the proposed frequency octupling architecture. LD: laser diode; PD: photo-diode; LO: local oscillator, (b) Argand diagram showing 16 paths of the parallel equivalent architecture where each segment represents the individual arm's RF phase and the phase information of it being differentially driven. Red defines $\sigma_p = 1$ and blue defines $\sigma_p = -1$, (c) The summation of the phasors lies on the same path forms a constellation of 16 points. For MITP bias, red defines $\rho_\alpha = 1$, blue defines $\rho_\alpha = -1$.

each stage. An abstract graph can be considered in which the vertices describe splitters (defined by their transmission matrices) and edges describe optical components in the arms such as active phase shifters driven by RF signals and or delays and pre-set phase biases. Selecting one port at a vertex as input and one port at a different vertex as output every possible path can be traced and summed. The total transmission can be represented as,

$$f(t) = \frac{1}{2^N}\sum \rho_\alpha \exp\{im[\textstyle\sum_{p=0}^{N-1}\sigma_p\cos(\omega_{RF}t + \Delta\emptyset_p)]\} \qquad (1)$$
$$\rho_\alpha = \textstyle\prod_{p=0}^{N-1}\alpha_p$$

where N is the no. of MZM stages, $m=(\pi V_{RF})/V_\pi$ is the modulation index, $\Delta\emptyset_p = (p\pi)/N$ (p=0, 1, 2, 3) is the phase shift of the p^{th} RF drive introduced to the p^{th} MZM and ω_{RF} is the RF angular frequency. The RF and optical phase differences between two arms of each differentially driven MZM are expressed by σ_p and α_p respectively. For the proposed system, $\alpha_p = \sigma_p = 1$ for the upper arm and $\alpha_p = \sigma_p = -1$ for the lower arm are defined for each MZM biased at MITP. Equation (1) can be characterized by employing

$$\textstyle\sum_{p=0}^{N-1}\sigma_p \exp\left[i\left(\omega_{RF}t + p\frac{\pi}{N}\right)\right] = r_\sigma \exp(i\theta_\sigma)\exp(i\omega_{RF}t) \qquad (2)$$

where r_σ and θ_σ define the phasor relationship of each path. Utilizing Fig. 1(b), Fig. 1(c) and the Jacobi-Anger expansion, the output can be expressed as

$$E_{out} = E_{in}[\{J_4(r_+m)+J_4(r_-m)\}\sin(4\omega_{RF}t) - \{J_{12}(r_+m)+J_{12}(r_-m)\}\sin(12\omega_{RF}t) + \{J_{20}(r_+m)+J_{20}(r_-m)\}\sin(20\omega_{RF}t)\ldots.] \qquad (3)$$

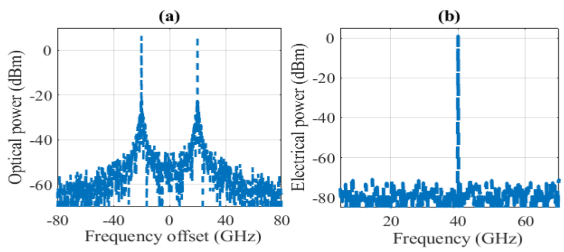

Fig. 1. (a) Optical spectrum and (b) electrical spectrum of the frequency 8-tupling signal

where J_n is the Bessel function of the first kind of order n, $r_+=(2.828)\cos(\pi/8)$ and $r_-=(2.828)\sin(\pi/8)$. Equation (3) suggests the suppression of all the sidebands alongside the optical carrier by design except the odd multiples of the 4th harmonic. The effects of the unsuppressed higher-order harmonics can be neglected for $m<\pi$. Biasing all MZMs at MATP can be employed to perform frequency 16-tupling [7] but then the operating range in terms of modulation index becomes narrow because of the emergence of carrier breakthrough, which can be deduced from Fig. 1(c). All paths are added with same optical phase so nullification of $J_0(mr_\pm)$ cannot be obtained by design.

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 100 mW is used as the optical input. A 5 GHz sinusoidal RF drive signal is applied with appropriate RF phase. A PIN diode with a responsivity of 0.8 A/W is used for detecting the output signal.

The optical and electrical spectra at the output of the configuration are shown in fig. 2. As shown in fig. 2(a), the power of the two 4th order harmonics is 70 dB higher than that of the other pronounced unwanted harmonics. The optical carrier and all the sidebands except the odd multiple of 4th order are effectively suppressed. After beating at the photodetector, a pristine frequency component at 40 GHz is obtained as shown in fig. 2(b).

A comparison is made among the proposed architecture and two other frequency 8-tupling configurations to evaluate the RF power efficiency. From fig. 3, it can be obtained that the proposed cascaded architecture biased at MITP can perform more efficiently at low RF input. The architecture utilizing 2 cascaded MZMs, each biased at MATP shows narrow operating range as a specific RF input is needed to suppress the carrier [8]. A wider operating range in term of modulation index can be achieved by the parallel architecture at the expense of high RF drive [9]. Besides, the outer MZI should be biased at MITP to suppress carrier,

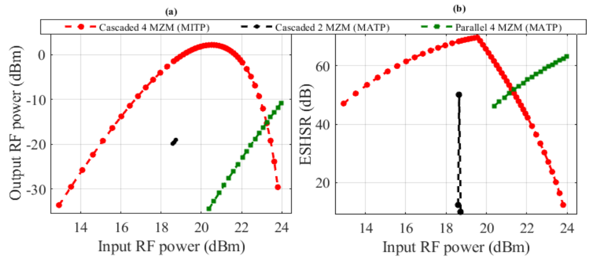

Fig. 3. Comparison between the proposed cascaded architecture and two other architectures in terms of (a) RF input-output power and (b) ESHSR.

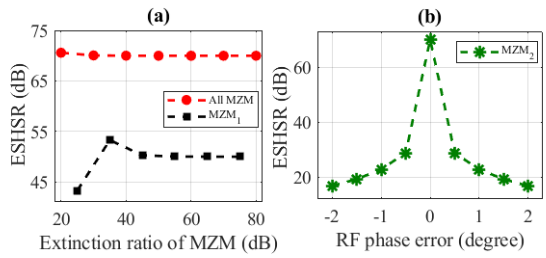

Fig. 4. Effects on ESHSR due to the variation of (a) extinction ratio of MZMs and (b) RF phase angle

which needs employment of optical delay line or directional coupler, triggering additional excess optical loss relative to the proposed cascaded architecture.

The effects of unbalanced splitting ratio intrinsic to the MZM is checked. As shown in fig. 4(a), a flat response in terms of ESHSR can be observed when all the MZMs are having same finite extinction ratio. The situation changes when the extinction ratio is different for each MZM. ESHSR greater than 40 dB can be achieved when the extinction ratio of MZM_1 is 25 dB and for others, it is kept at 30 dB. Strong dependence on precise RF drive phase is observed in fig. 4(b). Operation with ESHSR greater than 20 dB can be achieved with ±1□ drift in RF drive phase.

IV. Conclusion

In summary, an optical millimeter wave generation architecture is proposed as an energy efficient method with ~7 dB RF advantage compared to functionally equivalent circuit. Moreover, the circuit requires no optical or electrical filtering and careful adjustment of RF drive level for sideband suppression. The proposed architecture can be integrated in any material platform that offers linear electro-optic modulators.

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