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# Theoretical analysis and modeling of a photonic integrated circuit for frequency 8-tupled and 24-tupled millimeter wave signal generation

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A photonic circuit design for implementing frequency 8-tupling and 24-tupling is proposed. The front- and back-end of the circuit comprises  $4 \times 4$  MMI couplers enclosing an array of four pairs of phase modulators and  $2 \times 2$  MMI couplers. The proposed design for frequency multiplication requires no optical or electrical filters, the operation is not limited to carefully adjusted modulation indexes, and the drift originated from static **DC** bias is mitigated by making use of the intrinsic phase relations of multi-mode interference couplers. A transfer matrix approach is used to represent the main building blocks of the design and hence to describe the operation of the frequency 8-tupling and 24-tupling. The concept is theoretically developed and demonstrated by simulations. Ideal and imperfect power imbalances in the multi-mode interference couplers, as well as ideal and imperfect phases of the electric drives to the phase modulators are analyzed. © 2013 Optical Society of America

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The efficient generation and distribution of millimeter wave (mm-wave) carriers over optical fibers has been an intensive topic of research for various applications and has become one of the key aspects towards the deployment of high-capacity coherent radio-over-fiber systems. Owing to its conceptual simplicity, the remote heterodyne beating of two phase correlated wavelengths impinging onto a high speed photo-receiver is a feasible approach that facilitates the generation of frequency tunable mm-wave carriers. Among different techniques such as optical injection-locking in master-slave laser architectures, and optical-electrical phase loops, the external optical modulation is an attractive and cost effective solution for the creation of two phase correlated wavelengths because their frequency difference can be made equal to an integer factor of the frequency of an electrical local oscillator. Consequently, tunable mm-wave carriers whose frequency is several times larger than that of an electrical local oscillator can be generated. One of the first experimental demonstrations of a frequency doubler based on the remote heterodyne concept was reported over 20 years ago using a single laser source together with a LiNbO<sub>3</sub> Mach-Zehnder modulator (MZM) to obtain a narrow line-width 36 GHz electric signal with a peak power around -50 dBm and signal-to-noise ratio (SNR) of over 40 dB [1]. Thereafter, different higher order multiplication factors have theoretically and experimentally been reported, achieving frequency quadrupling [2]-[4], sextupling [5]-[6], octupling [7]-[10] and beyond [11]-[13]. Regarding frequency quadrupling, for instance, a MZM biased at the minimum transmission point to suppress the odd order side-bands is used in addition with an optical notch filter to generate a 32-50

GHz mm-wave with a peak power under -30 dBm and SNR of over 60 dB [2]. An architecture comprising two cascaded MZMs biased at the minimum transmission point and a tunable optical delay line between them is used in [3] to generate ~32 GHz carriers with under -50 dBm peak power and ~40 dB SNR out of an 8.2 GHz electrical oscillator. An integrated design comprising two MZMs biased at full point and placed in the arms of an outer MZM biased at the null point is proposed as an optical filter-less approach to obtain second order side bands with an optical and harmonic distortion suppression ratio of more than 36 dB, generating a -30 dBm mm-wave carrier at 40 and 72 GHz [4]. Configurations based on two cascaded two-electrode MZMs differentially driven by a 10 GHz local oscillator [5] and based on a polarization modulator and wavelength-fixed optical notch filter [6] have been proposed as frequency sextupling approaches to generate tunable carriers from 18 to 114 GHz. Similar designs based on nested MZMs [7], dual-parallel MZMs in combination with notch filters [8], cascaded MZMs with a tunable optical delay line between the modulators [9], or four-parallel phase modulators [10] have been experimentally and theoretically studied for frequency octupling. Higher frequency multiplication factors have been investigated. For instance, second order harmonics out of a dual-parallel MZM are used to implement degenerate four-wave mixing in a semiconductor optical amplifier to achieve frequency 12-tupling [11]. Two-electrode dual-parallel MZM with carefully adjusted radio frequency drive signals has also been studied and demonstrated by numerical simulations for 12-tupling frequency multiplication [12]. A configuration of three MZM in

parallel has been proposed for frequency 6-tupling, 12-tupling, and 18-tupling depending upon the bias conditions on the modulators [13].

A constant feature in almost all the above mentioned reports is the use of discrete components, the need of bias points as well as large and carefully adjusted drive signals going to the MZMs, and optical filtering stages to suppress the optical carrier or unwanted harmonics. An 8-fold frequency multiplication integrated design overcoming the drift caused by **DC** voltages and the elimination of optical filters remains challenging. In this work, a **DC** bias-less and filter-less photonic integrated circuit for the optical generation of frequency 8-tupled and 24-tupled mm-waves is proposed. The front- and back-end of the proposed circuit comprises  $4 \times 4$  multi-mode interference (MMI) couplers enclosing an array of four pairs of phase modulators and  $2 \times 2$  MMI couplers. Taking advantage of the phase relationships between the input and output signals in the  $4 \times 4$  MMI coupler and combiner [14], as well as the relative phase of the electric local oscillator driving the phase modulators, it is theoretically shown that the photonic circuit performs the 8-fold multiplication of the electric local oscillator frequency. The proposed circuit overcomes some of the demerits of previously reported frequency 8-tupling architectures because it requires no **DC** bias and its operation is not restricted to relatively large and carefully adjusted modulation indexes for suppression of unwanted harmonics. The concept is demonstrated by computer simulations on Virtual Photonics Inc. software package. Ideal and imperfect conditions such as power imbalances and phase relationships are analyzed to account for realistic MMIs and interconnecting waveguides. In addition, it is demonstrated theoretically and by simulations that frequency 24-tupling can also be

achieved after certain conditions of the drive local oscillator. The proposed architecture is naturally amenable to photonic integration due to the mature design and fabrication of MMIs and the rapidly advancing demonstrations of phase modulators based on silicon, InGaAsP, or silicon-organic hybrid materials [15]-[17].

A schematic diagram of the proposed photonic circuit is illustrated in Fig. 1(a) and is inspired in our former work [18], where it has been demonstrated that an abridged circuit configuration performs as a single side-band modulator and frequency up-conversion mixer. The photonic circuit architecture here presented comprises eight phase modulators situated in the arms between an interconnected  $4 \times 8$  distribution tree and a complementary  $8 \times 4$  combination tree. The  $4 \times 8$  distribution tree is formed by an outer stage consisting of a  $4 \times 4$  MMI coupler followed by an inner stage consisting of parallel pairs of  $2 \times 2$  MMI couplers, each with one complementary port unused. The  $8 \times 4$  combination tree is a reciprocal structure of the distribution tree. As shown in Fig. 1(b), each pair of phase modulators is combined with the inner stage of  $2 \times 2$  MMIs in a Mach-Zehnder Interferometer configuration that operates as a standard MZM when driven differentially. For given phase relations of the drive signal reaching each phase modulator, the upper and lower output ports of the MZMs produce odd and even harmonics (including the optical carrier), respectively. Owing to the complementary phases between the intermediate output ports  $d_2$  in the four MZMs and the phase relationships of the output  $4 \times 4$  MMI, constructive and destructive interference produce  $\pm 4$ -th harmonics with optical carrier suppression in port  $D_2$ . After photo detection, the photonic circuit here proposed performs the 8-fold and 24-fold multiplication of the local oscillator frequency driving the phase modulators.

The output of the high order frequency multiplication circuit can be obtained by using the transfer matrix for each element in Fig. 1. Following the development in [18], the transfer matrix for each MZM<sub>A,B,C,D</sub> is as follows:

$$\begin{bmatrix} d_1 \\ d_2 \end{bmatrix} = i \begin{bmatrix} \sin(\varphi) & -\cos(\varphi) \\ -\cos(\varphi) & -\sin(\varphi) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad (1)$$

where  $\varphi = \pi V/V_\pi$  is the optical phase shift impressed to the phase modulator of a MZM with switching voltage of  $V_\pi$  by the application of a differential signal with amplitude  $V$ . Using Eq. (1) and assuming ports  $a_2$  and  $d_1$  are unused for the target application, the output of the circuit can be represented by:

$$\begin{bmatrix} D_0 \\ D_1 \\ D_2 \\ D_3 \end{bmatrix} = -i [T] \begin{bmatrix} \cos\varphi_A & 0 & 0 & 0 \\ 0 & \cos\varphi_B & 0 & 0 \\ 0 & 0 & \cos\varphi_C & 0 \\ 0 & 0 & 0 & \cos\varphi_D \end{bmatrix} [T] \begin{bmatrix} A_0 \\ A_1 \\ A_2 \\ A_3 \end{bmatrix} \quad (2)$$

where:

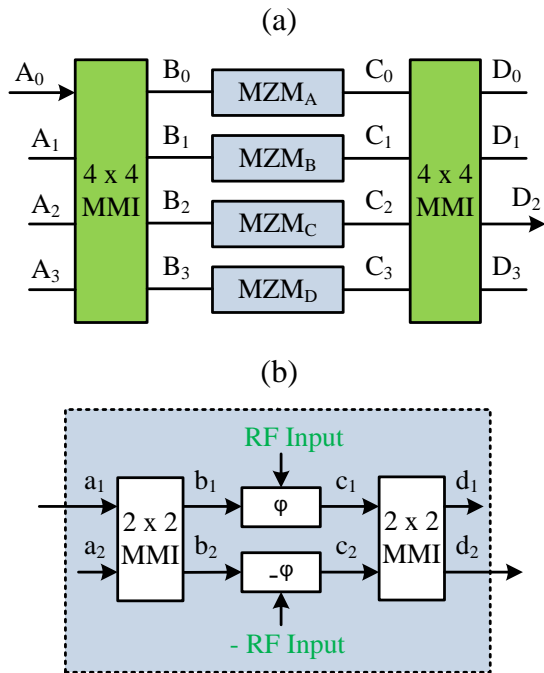


Fig. 1. (a) Schematic diagram of the proposed frequency 8-tupling and 24-tupling multiplication circuit. (b) Mach-Zehnder Interferometer driven **differentially**.

$$T = \frac{1}{2} \begin{bmatrix} 1 & \zeta & -\zeta & 1 \\ \zeta & 1 & 1 & -\zeta \\ -\zeta & 1 & 1 & \zeta \\ 1 & -\zeta & \zeta & 1 \end{bmatrix} \quad (3)$$

is the transfer matrix of the  $4 \times 4$  MMI coupler and combiner, with  $\zeta = e^{i\pi/4}$  [14] and  $\varphi_{A,B,C,D}$  are the optical phase shifts of each MZM<sub>A,B,C,D</sub> respectively. Developing (2) and (3), the output in port  $D_2$  is expressed as:

$$D_2 = \frac{-iA_0\zeta}{4} (-\cos\varphi_A + \cos\varphi_B + \cos\varphi_C + \cos\varphi_D) \quad (4)$$

Assume the modulating signals  $V_n = V_{RF} \cos(\omega_{RF}t + \theta_n)$  driving each MZM have a progressive  $\pi/4$  phase shift, where  $\omega_{RF}t$  and  $\theta_n$  are the dynamic and static phases of the modulating signals, respectively, and  $n$  denotes the index A, B, C, and D of each MZM. Using the Jacobi-Anger expansion, each term in (4) can be represented as:

$$-\cos(m\cos(\omega_{RF}t)) = -J_0(m) - 2 \sum_{n=1}^{\infty} (-1)^n J_{2n}(m) \cos(2n\omega_{RF}t) \quad (5)$$

$$\cos(m\cos(\omega_{RF}t) + \pi/4) = J_0(m) + 2 \sum_{n=1}^{\infty} (-1)^n J_{2n}(m) \cos(2n\omega_{RF}t + \pi/4) \quad (6)$$

$$\cos(m\cos(\omega_{RF}t) + \pi/2) = J_0(m) + 2 \sum_{n=1}^{\infty} (-1)^n J_{2n}(m) \cos(2n\omega_{RF}t + \pi/2) \quad (7)$$

$$\cos(m\cos(\omega_{RF}t) + 3\pi/4) = J_0(m) + 2 \sum_{n=1}^{\infty} (-1)^n J_{2n}(m) \cos(2n\omega_{RF}t + 3\pi/4) \quad (8)$$

where the arguments  $0, \pi/4, \pi/2,$  and  $3\pi/4$  in the modulating cosine signals are the static progressive phases. Developing the right-hand side terms in Eqs. (5) to (8), substituting them into Eq. (4) and eliminating common terms, the signal at the output port  $D_2$  can be reduced to:

$$D_2 = \frac{iA_0\zeta}{4} [J_4(m) \cos(4\omega_{RF}t) + J_4(m) \cos(-4\omega_{RF}t) + J_{12}(m) \cos(12\omega_{RF}t) + J_{12}(m) \cos(-12\omega_{RF}t) + \dots] \quad (9)$$

where  $m = \pi V_{RF}/V_\pi$  is the modulation index of the MZMs, and  $J_n(\cdot)$  is the Bessel function of first kind with order  $n$ . From Eq. (9), it can be seen that all the  $n$ -th order harmonics are suppressed, except those for  $n = 4x$ , where  $x$  is an odd integer. Moreover, for modulation indexes  $m \leq 6.5$ , only the terms  $J_4(m)$  are non-negligible and hence the circuit performs as a frequency 8-tupling after the output is passed through a square-law photo-diode. Note for modulation index around 11, the term  $J_{12}(m)$  becomes dominant and eventually the circuit can perform the frequency 24-tupling of an electric local oscillator.

The operation of the proposed design in Fig. 1(a) is demonstrated by implementing computer simulations in Virtual Photonics Inc. (VPI) software package. A continuous wave DFB laser diode set at a wavelength of 1550 nm with a line-width of 200 kHz and power of 10 mW is used as the optical input. From the Photonic

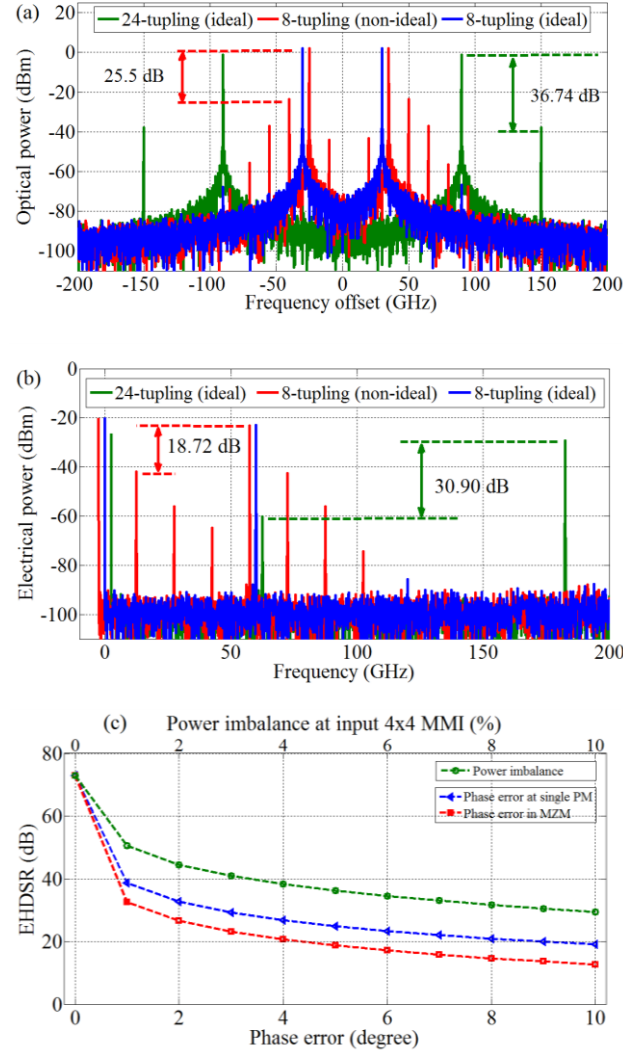


Fig. 2. (a) Optical spectrum of the signal at output port  $D_2$ . (b) Electrical spectrum after photo detection. (c) EHDSR for power imbalances in the input  $2 \times 2$  MMI and phase errors in the phase modulators. For visualization, plots for 24-tupling (ideal) and 8-tupling (non-ideal) have been frequency shifted by  $\pm 2$  GHz.

Integrated Circuit library in VPI,  $4 \times 4$  and  $2 \times 2$  MMIs are configured as couplers and splitters with proper power and phase relations according to the self-imaging principle [14]. Ideal phase modulators are used. A 7.5 GHz sinusoidal drive signal is applied to the phase modulators. Since the circuit operation is not restricted to carefully adjusted amplitude of the drive signal, modulation indexes from 2.5 to 7.5 can be set. As an illustrative example for maximised frequency 8-tupling, the modulation index is set to  $m = 5$ , which results in an amplitude of 1.6 V for phase modulators with  $V_\pi = 1$  V. The phase of the drive signals at the input of the eight phase modulators (from top to bottom) is set to  $0$  &  $\pi$  (MZM<sub>A</sub>),  $\pi/4$  &  $5\pi/4$  (MZM<sub>B</sub>),  $\pi/2$  &  $3\pi/2$  (MZM<sub>C</sub>) and  $3\pi/4$  &  $7\pi/4$  (MZM<sub>D</sub>). In the ideal case of perfect power split and phase relations among all the MMI ports and above mentioned phase relations of the drive signals



applied to the phase modulators, frequency 8-tupling is achieved. As shown Fig. 2(a), 4-th harmonics at  $\pm 30$  GHz ( $4 \times 7.5$  GHz) without optical carrier and over 69 dB suppression ratio from unwanted harmonics are obtained. After photo-detection, a clean frequency component at 60 GHz with electrical harmonic distortion suppression ratio (EHDSR) of over 65 dB is obtained and shown in Fig. 2(b), achieving thus the 8-fold frequency multiplication of the input drive signal. To take into account practical inaccuracies such as minor phase errors and power imbalances in the design or fabrication of the MMIs, as well as the lengths of the waveguides interconnecting the various components in the proposed photonic circuit, the performance of the frequency 8-tupled signal is analyzed in non-ideal conditions. The EHDSR that is obtained after accounting for power imbalances in port  $B_0$  of the input  $4 \times 4$  MMI from ideal to 10 % is shown in Fig. 2(c). Similar performance is obtained in the simulations for power imbalances in other ports of the input  $4 \times 4$  MMI. The operation of the 8-tupling circuit taking into account phase errors from  $0^\circ$  (ideal case) to  $10^\circ$  in both a single phase modulator (i.e.,  $0 \pm 10^\circ$  in the top phase modulator) and in a differential MZM (i.e.,  $(0 \ \& \ \pi) \pm 10^\circ$  in MZM<sub>A</sub>) is shown in Fig. 2(c). As also discussed in [18], simulation results indicate the appearance of unwanted harmonics arises at a larger extent due to the phase errors in the drive signals reaching the differential modulators. The length of the waveguides connecting the drive signal to the phase modulators can hence be considered as the critical design point in the proposed photonic circuit. Nevertheless, an EHDSR of over 30 dB is obtained for 5% error in the  $4 \times 4$  MMI power imbalance and over 18 dB for  $5^\circ$  phase error in the drive signals, overcoming previously reported values for 8-fold frequency multiplication.

As illustrated in Figs. 2(a) and 2(b), frequency 24-tupling can also be achieved when setting a modulation index at  $m \approx 11$  with the same frequency and ideal phase relationships of the drive signals as above. In this case, 12-th harmonics at  $\pm 90$  GHz with optical carrier suppression are obtained. Despite the appearance of frequency components  $\pm 60$  GHz apart from each of these harmonics, an optical carrier and harmonic distortion suppression ratio of over 36 dB is obtained.

In summary, a **DC** bias-less and filter-less photonic circuit design for implementing frequency 8-tupling and 24-tupling is proposed, analyzed and verified by software simulations. The proposed design overcomes the demerits of previously reported works because the frequency multiplication scheme requires no optical or electrical filters, the operation is not limited to carefully adjusted modulation indexes, and the drift originated from static dc bias is mitigated by making use of the intrinsic phase relations of multi-mode interference couplers. After analyzing the simulation results, the frequency 8-tupling and 24-tupling with optical carrier and harmonic distortion ratio of over 30 dB is achieved for inaccuracies on the 5% power imbalance of the input MMI and over 18 dB for  $5^\circ$  phase errors on the drive signals. The implementation of the proposed frequency multiplier in a photonic integrated circuit seems feasible because of the mature fabrication platforms for MMIs and the rapidly

advancing demonstrations of phase modulators based either on silicon, InGaAsP, silicon-organic materials, or hybrid integration technologies.

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