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A photonic frequency octo-tupler with reduced RF drive power and extended spurious sideband suppression

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ABSTRACT

A Mach-Zehnder interferometer with each arm containing a pair of Mach-Zehnder modulators (MZM) in series is proposed as a means of optoelectronic frequency multiplication (octo-tupling and 24-tupling). All harmonics including the carrier are suppressed except those with order equal to an odd multiple of four. The circuit requires no electrical or optical filters. There is no requirement to carefully adjust the modulation index to achieve correct operation of the octo-tupler. A transfer matrix representation is used to describe the operation of the architecture. The theoretical predictions are validated by simulations performed using an industry standard software tool. The simulations also allow an assessment of the impact on the circuit operation of deviations from the ideal of its components such as the finite extinction ratio of the MZMs, power imbalances and phase error at the couplers and phase error of the applied RF signals. Finally, a comparison is made with an alternative functionally equivalent single-stage parallel MZM circuit. One finding is that the intrinsic conversion efficiency of the proposed circuit is improved by 3 dB over the alternative. The proposed circuit is suitable for integration in material platforms supporting linear electro-optic modulation such as $LiNbO_3$, silicon, III–V or hybrid technology.

1. Introduction

The fundamental operational principle at the heart of microwave photonics is the heterodyne beating at a high speed photodetector of two optical carriers separated in frequency, which offers a conceptually simple means of generating a widely-tuneable microwave carrier. To ensure the generation of a spectrally pure microwave carrier, the two optical carriers must be correlated in phase. Although there are various ways by which correlated optical carriers may be generated, external modulation of a laser is particularly attractive because it offers high-stability tuneable spectrally-pure microwave carriers with system simplicity. The basic principle is to phase-modulate an optical carrier by a radio frequency (RF) electrical carrier via a suitable electro-optic modulator. The modulation results in an optical spectrum containing a multitude of phase correlated lines separated by the RF frequency.

Numerous circuit architectures have been conceived [1–18] that contain several phase modulators driven from the same optical and electrical sources but with carefully chosen relative phase-shifts combined in a network such that only two optical lines separated by a desired multiple of the RF frequency have significant amplitude at the output port. The majority of the circuits proposed [1–12] employ essentially a single stage generalized Mach-Zehnder interferometer (GMZI) architecture in which N phase modulators are interconnected by a 1:N splitter and a N:1 coupler. When N is even, the individual phase modulators may be paired and the basic element may be considered to be a dual-drive or, most often, a differential-drive Mach-Zehnder Modulator (MZM). Circuit designs for frequency multiplication by quadrupling [1–3,13,14], sextupling [4,15,17], octo-tupling [5–9,16,17] and by greater factors [10–12] have been reported. The use of discrete components; the need for static DC bias points; and the use of carefully adjusted electrical drive levels or optical filtering to suppress a particular unwanted harmonic are among the most common demerits of these designs. A notable advance is the report [8,9] of a single stage parallel MZM architecture that provides a DC bias-less and filter-less frequency octo-tupler which can be operated over a wide range of modulation index (m~2 → 7.30), thus overcoming the requirement of precise RF drive adjustment. The circuit proposed in this paper provides a further advance on this architecture by reducing the RF power required by 50%.

A lesser number of proposals have considered two-stage architectures in which the basic element, i.e., MZMs, are connected in series [13–17] or both in series and parallel [18]. Circuit designs for frequency multiplication by quadrupling, sextupling and octo-tupling using a two-stage cascade MZM structure are proposed in references [13–17]. The MZM modulators are biased at the minimum transmission point (MITP) with the RF drive having a 90°

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Table 1
Summary of the previous work related to frequency multiplication.

Reference	*Multiplication factor*	*Exp/SIM*	*Comment*
O'Reilly 1991 [1]	2	Exp	MZM is biased at MITP to suppress even order harmonics leaving ±1 orders significant in strength.
Qi 2005 [2]	4	Exp	FBG used to suppress carrier
Lin 2008 [3]	4	Exp	Dual-parallel Mach Zehnder Modulator (DP-MZM). Outer MZI biased at MITP
Shi 2010 [4]	6	Sim	DP-MZM Both the sub-MZMs are biased at MITP, outer MZI biased at MATP. RF drive is adjusted to suppress the 1 order harmonics. 5 order is suppressed by the adjustment of RF drive phase shift.
Zhang 2012 [5]	8	Exp	Orders 1, 2, 3 are suppressed. Order 0 is suppressed by FBG. Leaving ±4 orders significant in strength.
Ma 2008 [6]	8	Sim	DP-MZM RF drive level adjusted to suppress carrier
Guemri 2014 [7]	8	Sim	Orders 1, 2, 3 are suppressed. Order 0 is suppressed by adjustment of the RF drive level.
Hasan 2014 [8]	8, 24	Sim	4 parallel MZM deployed between two 4 × 4 MMIs. The circuit can be operated for a wide range of modulation index (∼2 to ∼7.50).
Hasan 2014 [9]	8	Sim	2 parallel DP-MZM between y-splitter/combiners. The circuit can be operated for a wide range of modulation index (∼2 to ∼7.50).
Shih 2010 [10]	12	Sim	DP-MZM is used with a four wave mixing technique. An optical interleaver is used to suppress unwanted harmonics.
Zhu 2013 [11]	12	Sim	Orders 0, 1, 3, are suppressed. Order 2 is suppressed by adjustment of the RF drive. Leaving ±6 orders significant in strength
Chen 2011 [12]	6, 18	Sim	Unsuppressed orders are −9, −3, 3, 9. Order 3 suppressed by adjustment of RF drive level to achieve ×18.
Zhang 2007 [13]	4	Exp	2 MZM in series. MZMs biased at (MITP, MITP)
Chi 2008 [14]	4	Exp	2 MZM in series. MZMs biased at (MITP, MITP); tunable optical delay between stages
Mohammed 2008 [15]	6	Exp	2 MZM in series. MZM biased (MITP, MATP) or (MATP, MITP); RF drive level adjusted to suppress unwanted orders.
Li 2010 [16]	8	Exp	2 MZM in series. Tunable optical delay is used. RF drive level adjusted to suppress unwanted orders.
Li 2010 [17]	4, 6, 8	Exp	2 MZM in series. FBG is used and tunable optical delay is used to suppress unwanted orders.
Gao 2014 [18]	6	Exp	Intensity modulator in series with DP-MZM. Controlled DC bias is used to suppress the unwanted harmonics

phase difference between the stages to obtain the frequency quadrupling function [13]. An equivalent effect as the quadrature RF drive to the second stage is obtained with in-phase RF drive by inserting a tuneable optical delay line to adjust the relative phase of the sidebands generated by the first stage [14]. By setting the first MZM at the MITP and the second MZM at the maximum transmission point (MATP) or vice-versa frequency sextupling is achieved [15,17]. By biasing both the MZM at the MATP frequency octo-tupling is achieved with appropriate adjustment of the tunable optical delay line and RF drive level [16,17]. Although a single stage parallel MZM structure has been found [8,9] capable of filterless and dc bias-less octo-tupling without the requirement of precise adjustment of RF drive and/or tunable delays; as far as the authors are aware, a two stage MZM with series-parallel structure that provides the same function for 50% less RF power is not known in the prior art. A summary of the works mentioned in the preceding is given in Table 1.

In this work, a Mach-Zehnder interferometer with each arm containing a pair of Mach-Zehnder Modulators in series is proposed for the first time as an optoelectronic means of microwave frequency octo-tupling. The optical carrier and all sidebands except those with orders equal to an *odd* integer multiple of four are naturally suppressed. This is an advance on the prior art where suppression of all orders except those that are *any* integer power of four only has been shown which necessitates the critical adjustment of the drive level to suppress the carrier. The circuit requires no electrical or optical filters. There is no requirement to carefully adjust the modulation index to achieve correct operation of the octo-tupler rather it can be operated over a wide range of modulation index i.e. (m~2 → 7.30). Moreover the circuit requires 50% of the RF power required by the functionally equivalent single-stage parallel MZM architecture for the same output. If the RF drive is adjusted to suppress the fourth order sidebands, the same configuration can be used for frequency 24-tupling.

The paper is structured as follows. The circuit architecture is first described and its operation analysed theoretically using a transfer matrix approach. The theoretical predictions are then validated by the results of computer simulation using the Virtual Photonics Inc. software package. The simulation results are also presented to illustrate the impact on the circuit performance of the non-idealities encountered in practice such as power splitting imbalance of the optical couplers, optical phase imbalance and phase errors of the RF signals reaching the modulators. Finally, a comparison is presented with a functionally equivalent single stage GMZI as described in [9].

2. Principle of operation

The proposed circuit architecture, shown in Fig. 1, is formed by an outer Mach-Zehnder interferometer (MZI) biased at its MITP with each of its two arms containing a pair of MZMs in series; each

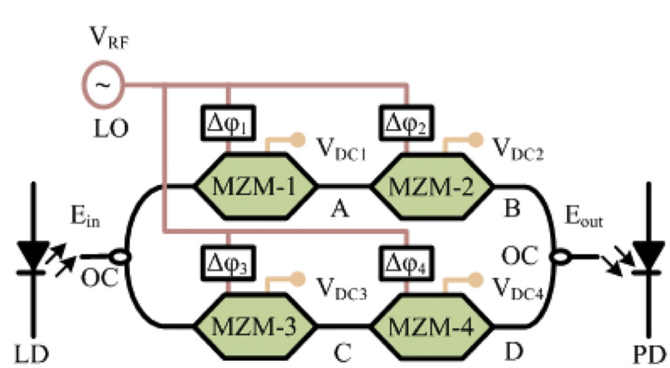

Fig. 1. Schematic diagram of the frequency octo-tupler circuit using Mach-Zehnder modulator in cascade; LD, Laser diode; OC, Optical coupler; RF, Radio frequency; LO, RF Local oscillator; PD, Photodiode.