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# A MMI-based ultra-linear high-gain modulator and its performance analysis

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ABSTRACT

An electric optical modulator including a $1\times2$ multimode interference (MMI) coupler and an integrated Mach–Zehnder Interferometer (MZI) modulator that consists of a microring and a Phase Modulator (PM) is suggested in this paper. Such a modulator can achieve large output RF gain and high linearity performance at the same time. Moreover, due to the application of MMI coupler, traditional direct current (DC) bias circuits can be omitted and the modulator's deterioration caused by the phase error can be decreased a lot, which leads to reduced device complexity and increased device stability. The presented numerical and simulation results confirm the advantages of the newly proposed modulator over conventional modulators (MZI, RAMZI and IMPACC). Further analysis manifests that the proposed modulator has good tolerance in two aspects. Firstly, the modulator has an inherent ability to mitigate the detrimental effects of microring waveguide loss on slope efficiency and linearity by simply adjusting the external RF power split ratio. Secondly, the application of the MMI device increases the modulator's tolerance for the phase deviation caused by some environmental factors.



## 1. Introduction

Radio over Fiber (RoF) or Radio over Free Space Optics (RoFSO) is well-established technique for the distribution of wireless communication signals in the future [1–6]. One key technique of RoF/RoFSO systems is the design of the electro-optic modulator which should maintain both high linearity and large output RF gain performance simultaneously in order to decrease high order distortion (such as the 3rd order inter-modulation distortion) and increase the ratio of signal to noise, especially, the instance of several RF signals modulating an optical carrier. Several linear electro-optic modulators have been presented by using different device configurations such as SOA-based modulators [4], MZI-based modulators [7–12], and Microring-based modulators [13]. Among these configurations, the MZI-based modulators are studied a lot and present high performance to some degree. The dual-signal MZI-based modulators [11] comprise of one modulator with two optical signals coupled to each arm respectively. The amplitudes and phases of the two input signals must be properly matched by using the predetermined values of the RF amplitude phase signal. The ring-assisted MZI-based modulators (RAMZI) [7,10,12] have been developed in recent years. The RAMZI couples microring(s) in the arm(s) of the MZI. This design can provide higher spurious free dynamic range (SFDR) performance but at the cost of a limited linearity range and stricter coefficient(s) control. The IMPACC couples a phase modulator on one arm of RAMZI and the modulating signals are fed onto the microring and the phase modulator according to an adjustable ratio. When the microring waveguide loss is taken into consideration, this design can maintain high SFDR but at the cost of the strict control of the direct current (DC) bias circuits [14] or a strict relationship between the lengths of the two arms of MZI [8]. As far as we know, a lot of schemes proposed earlier mainly focus on the linearity improvement, and they seldom have found a simple and compact application to realize both high output RF gain and linearity performance simultaneously. Actually, the high output RF gain performance of a modulator is desirable for analog links and necessary to be fulfilled. Some previous methods to improve RF gain performance require long arm lengths of MZI arms, which will unfortunately decrease the bandwidth of the device [10].

In this paper, we propose a novel and compact modulator composed by a Phase Modulator and Ring-Assisted MZI based on a $1\times2$ MMI coupler (MMI-PMRAMZI). Due to the exact split ratio and stable phase relations between the outputs, MMI couplers have been extensively researched as splitting elements ever since they were firstly suggested [15]. Since the relative phase between the two arms of MZI is provided by MMI coupler instead of the DC bias circuits, the complexity of the integrated MZI is reduced and the stability is also improved. Furthermore, as a potential structure which shows ultra-linearity, microring has been used in many

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applications to improve linearity. In addition, we apply a novel combination of microring and PM, which is able to provide both ultra-linear phase modulation and high slope efficiency simultaneously, thus effectively enhancing the sublinearity and RF gain performance of MZI. Moreover, by properly adjusting the external RF ratio applied on the microring and PM, MMI-PMRAMZI shows the ability to recover optimal SFDR value regardless of microring waveguide loss.

This paper is organized as follows. In Section 2, the theoretical model of the proposed modulator MMI-PMRAMZI is presented. Section 3 discusses and compares the device performances of MMI-PMRAMZI, MZI, RAMZI and IMPACC. In this section, two linearity criteria (linearity range $m$ and SFDR) and output RF gain performance are addressed. Section 4 compares the performances of RAMZI, IMPACC and MMI-PMRAMZI when microring loss and the DC biased circuits' shift from the normal operation point are taken into consideration, respectively. Section 5 discusses the importance of the relative phase and the proposed modulator's advantages. Section 6 gives a conclusion.

## 2. Principles

The structure of the key component in the MMI-PMRAMZI, i.e., $1\times2$ MMI coupler is shown in Fig. 1. It is composed of the input monomode waveguide (zone I), the multimode section (zone II) in which the interference effect of modal fields occurs, and the output monomode waveguides (zone III) [15–17]. The basic property of MMI coupler is self-imaging, which is the interference result of the motivated modes in the waveguide [18]. The $1\times2$ MMI coupler splits the light from the input monomode waveguide into two parts with equal intensities and different phases. The relative phases of the two parts are $\{0,\pi/2\}$, respectively. Thus the $1\times2$ MMI coupler can be represented as:

$$\begin{pmatrix} E_{out1} \\ E_{out2} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} e^{j0} \\ e^{j(\pi/2)} \end{pmatrix} E_{in} \tag{1}$$

where $E_{in}$ is the optical field amplitude at the input of MMI.

Using a $1\times2$ MMI coupler, the schematic diagram of MMI-PMRAMZI is shown in Fig. 2. A microring with circumference $d_r$ is coupled to one arm of the MZI and a PM with length $d_{pm}$ is coupled to the other arm. Input RF power is fed onto the electrodes of the microring and PM with a power split ratio of $F_1$:$F_2$, which can be externally controlled. Unlike traditional modulators, there is no DC bias voltage circuits applied to the MZI due to the use of $1\times2$ MMI coupler. The combination of the microring and the PM serves to provide the phase shaping effect to linearize the modulator's phase response.

Mathematically, the output lightwave of MMI-PMRAMZI can be expressed as:

$$E_{out} = \frac{E_{in}}{2}\left|a_r(\theta)\right| e^{-j\cdot(knL_1+\arg(a_r(\theta)))} + \frac{E_{in}}{2} e^{-j\cdot(knL_2+\theta_{PM}+(\pi/2))} \tag{2}$$

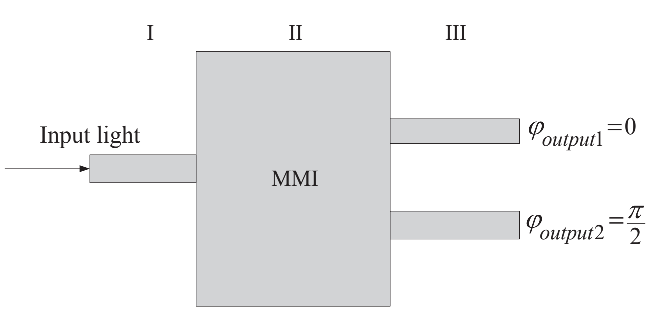


**Fig. 1.** Structure of $1\times2$ MMI.

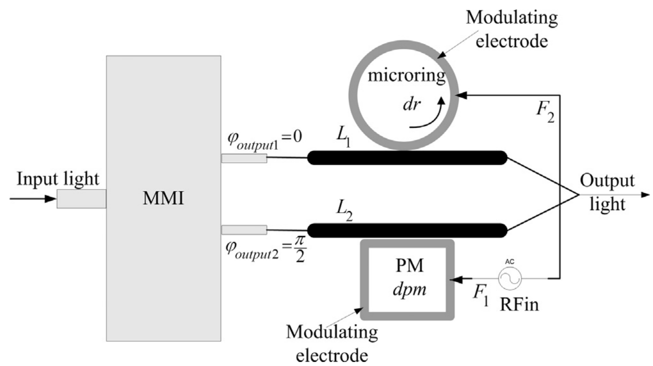


**Fig. 2.** Schematic diagram of the MMI-PMRAMZI.

where $E_{in}$ is the optical field amplitude of the input lightwave, $L_1(L_2)$ is the length in the straight part of upper (lower) arm of MZI, $|a_r(\theta)|$ and $\arg(a_r(\theta))$ are the amplitude response and phase response of the microring, respectively. $\theta_{PM}$ is the phase delay introduced by PM. The complex amplitude response of the microring is given by [19]:

$$a_r(\theta) = \tau - \kappa^2 \sum_{n=1}^{\infty} \tau^{n-1}(\alpha e^{-j\theta})^n = \frac{\tau - \alpha e^{-j\theta}}{1-\tau\alpha e^{-j\theta}} \tag{3}$$

where $\tau$ is the cross-coefficient of microring. $\alpha$ is the internal microring waveguide loss factor. Therefore, the corresponding amplitude response and phase response of the microring resonator are shown as follows [19]:

$$\left|a_r(\theta)\right| = \sqrt{\frac{\tau^2 - 2\alpha\tau\cos\ \theta + \alpha^2}{1-2\alpha\tau\cos\ \theta + \tau^2\alpha^2}} \tag{4}$$

$$\arg(a_r(\theta)) = \tan^{-1}\left(\frac{\alpha(1-\tau^2)\sin\theta}{\tau(1+\alpha^2)-\alpha(1+\tau^2)\cos\theta}\right) \tag{5}$$

The phase shift of microring $\theta$ and the phase delay introduced by PM $\theta_{pm}$ can be described as the following equations [20]:

$$\theta = kd_r(n_0 + \Delta n(V)) = \theta_{r0} + \Delta\beta d_r \tag{6}$$

$$\theta_{pm} = kd_{pm}(n_0 + \Delta n(V)) = \theta_{pm0} + \Delta\beta d_{pm} \tag{7}$$

$$\Delta\beta = \frac{\pi n_0^3 r \Gamma V_0}{\lambda g} \tag{8}$$

where $k$ is the propagation constant. $d_r$ is the circumference of the microring. $n_0$ is the effective index, and $\Delta n(V)$ is the function of applied voltage on the microring and PM. $\theta_{r0}$ and $\theta_{pm0}$ are the bias phases of microring and PM, respectively. $r$ is the Electro-optic (EO) coefficient. $\Gamma$ is the electrical-optical overlap integral. $V_0$ is the voltage amplitude. $\lambda$ is the free space optical wavelength and $g$ is the electrode gap.

Since the application of MMI coupler, the lengths of the arms $L_1$ and $L_2$ do not have to be set to fixed values and can be easily set as $L_1=L_2$. In addition, the microring resonator is required to work at an off-response state, i.e., $\theta_{r0}=\pi$, which is a salient feature of the MMI-PMRAMZI modulator indicating that it tolerates microring waveguide loss and its operation does not rely on high Q [9]. Therefore, in the absence of loss in the microring resonator, the transfer function (TF) of MMI-PMRAMZI can be simplified as the following equation:

$$T(\theta) = \frac{1}{2}\left\{1-\sin\left[\sqrt{F_1}\theta\cdot\frac{d_{pm}}{d_r} - \tan^{-1}\left(\frac{(\tau^2-1)\sin(\sqrt{F_2}\theta)}{2\tau+(1+\tau^2)\cos(\sqrt{F_2}\theta)}\right)\right]\right\} \tag{9}$$