A $LiNbO_3$ MICROWAVE-OPTOELECTRONIC MIXER WITH LINEAR PERFORMANCE

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ABSTRACT

A pair of $LiNbO_3$ based Mach-Zehnder interferometric modulators with performance upto 40 GHz are cascaded in series to build a microwave-optoelectronic mixer. The dynamic range of the mixer is significantly enhanced by biasing the devices at quadrature. The mixer has potential for application in wide-band fiber-optic communication systems.

I. INTRODUCTION

Recent advances in optoelectronic technology have rendered multi-gigahertz bandwidth fiberoptic systems practical. As efforts to enhance the bandwidth of these systems continues to grow, so does the demand for broadband optical sources. Recently, some ultra-broadband, low drive voltage (V_π) Ti:$LiNbO_3$ Mach-Zehnder interferometric external modulators have been reported [1,2]. These devices, by virtue of their DC switching characteristics are natural candidates for microwave mixing [3]. In this research, we investigate a novel microwave-optoelectronic mixer by cascading two Mach-Zehnder interferometric modulators in series. In such devices, broadband device performance either as a modulator or as a mixer is dependent on two key factors: microwave-optical velocity match and electrical leakage to substrate modes. For the devices reported here, microwave-optical velocity match was nearly achieved by employing thick ($\geq 15\mu$m) coplanar electrodes [4] and electrical leakage to substrate modes was eliminated by thinning the substrate [5]. Herein, we report the performance of the mixer and demonstrate linear operation by biasing both the interferometers at quadrature.

II. THEORY

Illustrated in a portion of fig. 1 is the layout of two Mach-Zehnder interferometers (MZ1 and MZ2) cascaded in series. For a single Mach-Zehnder interferometer, the output power P_0 normalized to that of the input is given by:

$$P_0 = \frac{1}{2}\left(1 + \cos\left[\phi_0 + \frac{\pi V}{V_\pi}\right]\right) \qquad (1)$$

where ϕ_0 is the intrinsic phase bias and V is the input voltage applied to the modulator. In this derivation since each interferometer in the cascaded pair is assumed to be biased at quadrature, $\phi_0 = 90^0$. If RF input signals $V_1 \sin \omega_1 t$ and $V_2 \sin \omega_2 t$ are the applied to MZ1 and MZ2 respectively, then P_0 of the pair is given by:

$$P_0 = \frac{1}{4}\left(1 + \cos\left[\frac{\pi}{2} + \frac{\pi V_1}{V_{\pi 1}} \sin \omega_1 t\right]\right) \left(1 + \cos\left[\frac{\pi}{2} + \frac{\pi V_2}{V_{\pi 2}} \sin \omega_2 t\right]\right) \qquad (2)$$

where $V_{\pi 1}$ and $V_{\pi 2}$ are the half-wave drive voltages of MZ1 and MZ2 respectively. Rewriting the above equation we get:

$$P_0 = \frac{1}{4}(1 - \sin[X_1 \sin \omega_1 t] - \sin[X_2 \sin \omega_2 t] + \sin[X_1 \sin \omega_1 t] \sin[X_2 \sin \omega_2 t]) \qquad (3)$$

where $X_1 = \frac{\pi V_1}{V_{\pi 1}}$ and $X_2 = \frac{\pi V_2}{V_{\pi 2}}$. Expanding the above equation in terms of Bessel functions and neglecting terms higher than third order, we get:

$$\begin{aligned} P_0 = \frac{1}{4}(1 &- [2J_1(X_1) \sin \omega_1 t + 2J_3(X_1) \sin 3\omega_1 t] \\ &- [2J_1(X_2) \sin \omega_1 t + 2J_3(X_2) \sin 3\omega_1 t] \\ &+ [2J_1(X_1) \sin \omega_1 t + 2J_3(X_1) \sin 3\omega_1 t] \\ &[2J_1(X_2) \sin \omega_1 t + 2J_3(X_2) \sin 3\omega_1 t]) \end{aligned} \qquad (4)$$

where J_n is the Bessel function of order n. From the above equation, for $X \ll 1$ we get (neglecting power terms higher than third order):

$$\begin{aligned} P_0 = \frac{1}{4}(1 &- X_1 \sin \omega_1 t - X_2 \sin \omega_2 t - \\ &\frac{X_1^3}{24} \sin 3\omega_1 t - \frac{X_2^3}{24} \sin 3\omega_2 t + \frac{X_1 X_2}{2} \\ &[\cos(\omega_1 - \omega_2)t - \cos(\omega_1 + \omega_2)t]) \end{aligned} \qquad (5)$$

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In the above equation, the powers associated with the third harmonic frequencies ($3\omega_1$ and $3\omega_2$) are small compared to the fundamental, sum and difference terms and hence can be neglected. It is obvious from above that the third order intermodulation (IM) frequency terms ($2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$) are not present when each interferometer of the cascaded pair is biased at quadrature. In conventional mixers, if $\omega_1 \approx \omega_2$ then the IM frequencies would be very close to the signal frequencies and hence cannot be filtered out. Also, the power associated with the IM frequencies being proportional to the cube of the input voltage increases rapidly with input power thereby limiting the dynamic range of the mixer. The cascaded Mach-Zehnder interferometeric pair, when biased at quadrature, does not suffer from such drawbacks and hence is an attractive candidate for microwave-optoelectronic mixing.

III. DEVICE PERFORMANCE

Illustrated in fig. 1 is a block diagram of the experimental set-up. In this experiment, cascading of the interferometric pair MZ1 and MZ2 was accomplished by use of a polarization preserving (PP) fiber. The devices were fabricated on z-cut $LiNbO_3$ substrates coated with a 0.9 μm SiO_2 buffer layer. The center strip widths of the coplanar waveguide electrodes were 8 μm, gapwidths were 15 μm and ground planes were 2 to 3 mm wide. Devices were fabricated on substrates 0.15 mm thick and 8 mm wide. The electrode interaction length was 24 mm. The average gold electrode thicknesses of MZ1 and MZ2 were 18 and 15 μm and the DC V_πs were 5 and 4.2 V respectively. The devices were designed for operation at an optical wavelength of 1.3 μm. From a fit to the electrical response of the device comprising conductor, dielectric and radiative losses [6] and considering the microwave-optical index mismatch (0.128 for MZ1 and 0.059 for MZ2) the derived optical responses of the devices are shown in fig. 2; error bars indicate uncertainity in calibrating out the response of the high-speed photodetector [5]. To the best of our knowledge, for devices that employ conventional thick electrodes for velocity matching, MZ2 is the best reported device. As shown in fig. 1, two synthesized RF sources operating at frequencies f_1 and f_2 are used to drive MZ1 and MZ2 respectively. Two 2-18 GHz amplifiers are used to obtain up to 10 dBm of device drive power and DC bias is applied via Bias-Ts. If the devices are not biased at quadrature, for input signals f_1 = 15.52 GHz and f_2 = 15.56 GHz, the following beat signals are obtained: $f_2 - f_1$ = 40 MHz and $2f_1 - f_2$ = 15.48 GHz and $2f_2 - f_1$ = 15.6 GHz. This is illustrated in fig. 3(a) where the spectra of just the signal and IM frequencies are shown; the spectrum of the difference signal at 40 MHz is shown in fig. 4(a). These spectra correspond to an applied input power of 10 dBm per device. However, for the same input power, when each device of the cascaded pair is biased at quadrature, the IM signals disappear. This is illustrated in fig. 3(b) where just the drive signals are present. We also extended the experiment to higher frequencies. For f_1 = 15 GHz and f_2 = 6 GHz the spectrum of the 9 GHz difference signal is shown in fig. 4(b). Although the devices perform very well to 40 GHz, we were limited in these experiments to less than 18 GHz due to equipment limitations. Also, it is worth noting here that since MZ1 and MZ2 are electrically decoupled, the isolation between their signal ports is almost infinite making them even more attractive for microwave mixing.

IV. CONCLUSIONS

We have presented a novel microwave-optoeletronic mixer by cascading a pair of Mach-Zehnder interferometric modulators in series. The dynamic range of the mixer is significantly enhanced when the devices are biased at quadrature and the signal ports of the mixer have infinite isolation. The circuit shows good potential for application in microwave-optoelectronic systems for operation up to 40 GHz.

V. ACKNOWLEDGEMENTS

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REFERENCES

[1] G.K. Gopalakrishnan et al.:'40 GHz low half-wave voltage Ti:$LiNbO_3$ intensity modulator', Electron. Lett., 1992, **28**, pp. 826-827.

[2] D.W. Dolfi and T.R. Ranganath:'50 GHz velocity-matched broad wavelength $LiNbO_3$ modulator with multimode active section', Electron. Lett., 1992, **28**, pp. 1197-1198.

[3] B.H. Kolner and D.W. Dolfi.:'Intermodulation distortion and compression in an integrated electrooptic modulator', Applied Optics, 1987, **26**, pp. 3676-3680.

[4] M. Seino et al.:'20 GHz 3 dB bandwidth Ti:$LiNbO_3$ Mach-Zehnder modulator', ECOC, 1990, paper ThG1-5.

[5] G.K. Gopalakrishnan et al.:'Electrical loss mechanisms in traveling wave $LiNbO_3$ optical modulators', Electron. Lett., 1992, **28**, pp. 207-209.

[6] G.K. Gopalakrishnan and W. K. Burns, unpublished data.

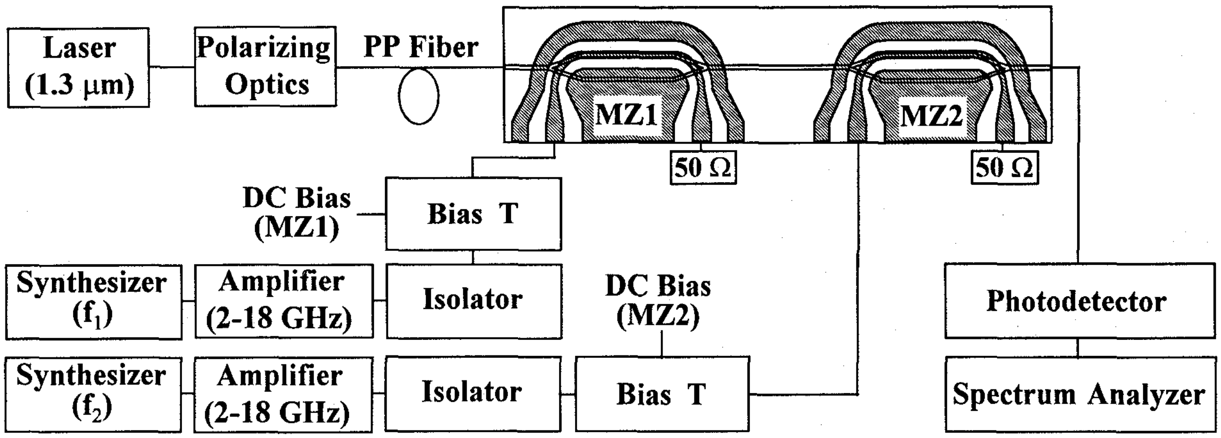


Fig. 1. Block diagram of experimental set-up.

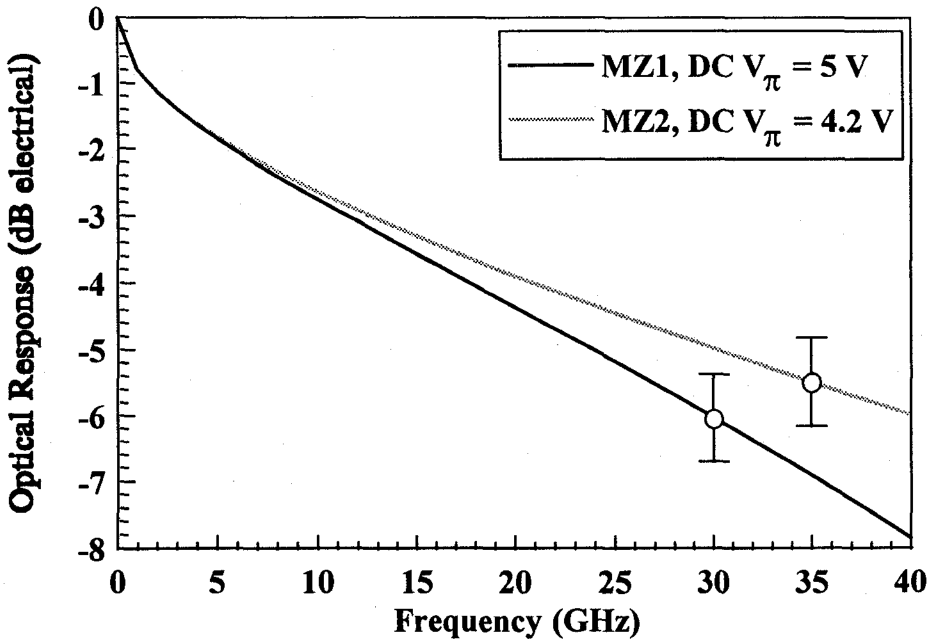
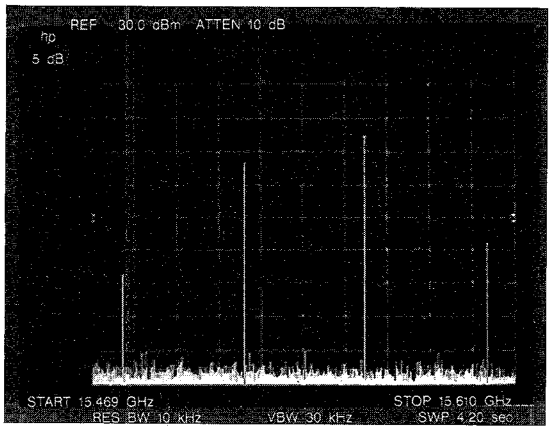
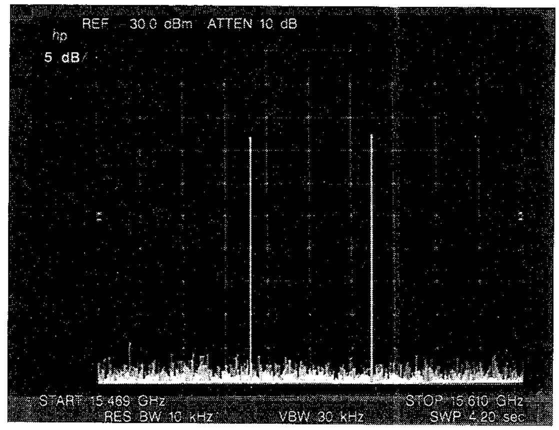


Fig. 2. Optical responses of MZ1 and MZ2.

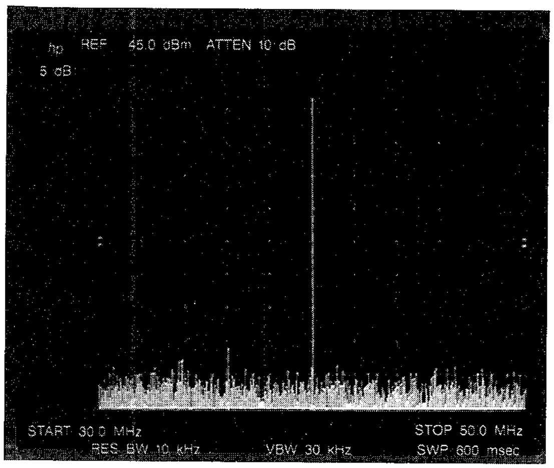


(a)

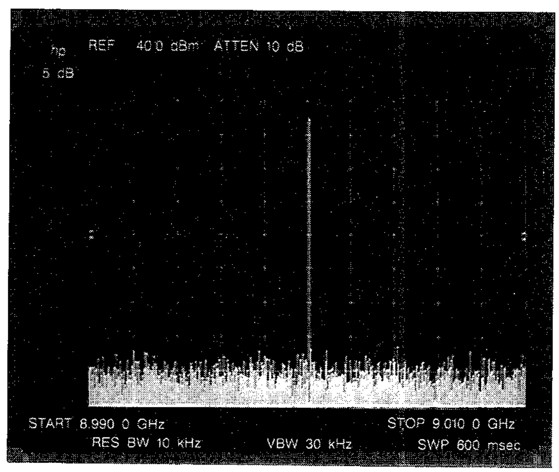


(b)

Fig. 3. Spectrum of signals (a) with and (b) without IM terms.



(a)



(b)

Fig. 4. Spectrum of difference signals at (a) 40 MHz and (b) 9 GHz.