Microwave Photonics Frequency-Converted Link Using Electroabsorption Devices

Y. Wu, D. S. Shin, W. S. C. Chang, and P. K. L. Yu

Abstract—**We propose a novel scheme to transmit high center frequency RF signals using electro-absorption devices (EADs) as frequency converters at the transmitter and the receiver. In this approach frequency heterodyning is employed for obtaining high center frequency. With the EAD as a detector/mixer at the receiver we demonstrated a smaller conversion loss than that of the conventional modulator/mixer. With EAD as a modulator/mixer at the transmitter and with two heterodyned lasers to generate an optical local oscillator (LO), we demonstrated a large reduction (~23dB) in conversion loss, and the transmission is not limited by the optical saturation of the EAD. This transmission scheme has optical single-side-band transmission feature which greatly relieves the fiber dispersion effect.**

Index Terms—**electroabsorption, frequency conversion, optoelectronic mixer, dispersion, optical saturation.**

I. Introduction

Analog fiber-optic links have been used as an alternative means to the conventional coaxial links for transmission at radio/microwave frequencies [1-5]. Typically in these optical links, the subcarrier multiplexed data modulates the intensity of light, which is then transmitted through very low-loss fiber. As the subcarrier frequency is increased to the millimeter wave frequency range, the chromatic dispersion of the standard single mode fiber causes a serious power penalty even after a short distance of transmission [6]. To alleviate this, a fiber-optic link that uses a down-converted subcarrier at an intermediate frequency (IF) near base band has been proposed [4,7]. Another effective approach to relieve the dispersion is to use the single-side-band transmission scheme which allows the transmission at high center frequency. [8]

A down-converted subcarrier requires frequency up-conversion at the remote base station for transmission at a desired frequency at the antenna. This can be done via an electronic mixer with a RF local oscillator (LO). Alternatively, using an optoelectronic mixer, the frequency conversions can be performed in the optical domain. [9]

In this paper, we analyze the principles of the electroabsorption device (EAD) that functions separately as a detector/mixer, a conventional modulator/mixer, and a heterodyned modulator/mixer. We show that heterodyned modulator/mixer not only enhances the conversion efficiency, it also facilitates single-side-band transmission. The analysis is found to agree with experimental results.

The EAD used in the experiment is an InAsP/GaInP multiple-quantum-well (MQW) modulator. As an detector/mixer, it has demonstrated a conversion loss of 18.4 dB at 10 mW optical local oscillator power. The same EAD operates as a modulator/mixer exhibits a higher conversion loss than the detector/mixer scheme. Experiment of the heterodyned modulator/mixer scheme shows a reduction of the conversion loss (~23 dB) when compared to the conventional modulator/mixer scheme. The maximum improvement is limited by the EAD's fiber-to-fiber insertion loss, the optical power handling of the fiber and that of the optical power handling of the remote photodetector, for instance, at the base station (BS).

The EAD as detector/mixer and/or proposed heterodyned

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modulator/mixer can function as a highly efficient optoelectronic mixer in a frequency agile RF link in which the center frequency can be tuned continuously at both the transmitter and the receiver. The output signal can be free of dispersion induced power penalty. The link and the overall system have more flexibility, robustness and the frequency encryption capability. The link efficiency penalty is estimated in this paper.

II. PRINCIPLES

1. Operating Principles of detector/mixer and modulator/mixer

A mixer is a three-port device. Fig. 1 shows the two different optical mixers using an EAD. They have the same input ports, one for optical LO (ω_{LO}) and another one for input electrical signal (ω_s). In the detector/mixer scheme the output electrical signal is directly obtained from the EAD. In the modulator/mixer scheme the signal is retrieved at the remote photodetector (PD).

1) The EAD as detector/mixer

As shown in Fig. 1a, when optical power P_{opt} is incident on an EAD biased at a voltage V_b, a photocurrent I_{ph} is generated via electroabsorption and it is a function of the incident optical power and the applied voltage:

$$I_{ph}(V_b, P_{opt}) = \eta(V_b) P_{opt} \quad (1)$$

where $\eta(V)$ is the detection responsivity of the EAD and is voltage dependent.

For simplicity, we assume that η is invariant with optical power. An RF signal voltage with a small amplitude v and frequency $f_s = \omega_s / 2\pi$ is superimposed to V_b. If the incident optical power P_{opt} of the optical LO is $P_0 + p\cos(\omega_{LO}t)$, using small signal analysis the device photocurrent is obtained as: where $\eta'(V_b)$ is a first-order derivative of η (with respect to V) evaluated at V_b. The first term in (2) yields a dc photocurrent while the second and the third terms give the photocurrent at ω_{LO} and ω_s respectively. The forth term corresponds to that of the up- and down-converted signals I_{ph}^{mix} at $\omega_{LO} \pm \omega_s$:

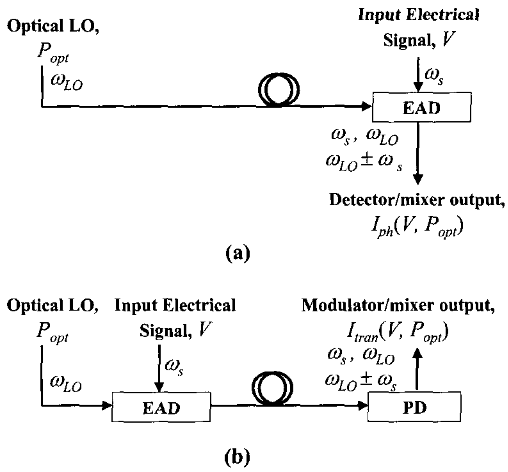


Fig. 1. Two Optoelectronic Mixer schemes using an EAD: (a) detector/mixer and (b) modulator/mixer.

$$\begin{aligned} I_{ph}(V, P_{opt}) &= \eta(V_b) P_0 + \eta(V_b) p \cos\omega_{LO}t \\ &+ \eta'(V_b) v P_0 \cos\omega_s t + \eta'(V_b) v p \cos\omega_s t \cos\omega_{LO}t + \cdots \end{aligned} \quad (2)$$

$$I_{ph}^{mix} = \frac{1}{2} \eta'(V_b) v p \cos(\omega_{LO} \pm \omega_s) t \quad (3)$$

The higher order derivatives of η contribute to the harmonic and intermodulation distortions of the link that uses EAD as detector/mixer. From (3), it is noted that the electroabsorption effect is essential in generating frequency-converted signals. In comparison, the EAD operating in pure photodetector mode [10] is typically biased to give a constant responsivity such that $\eta'(V_b) = 0$.

2) The EAD as a modulator/mixer

For this modulator/mixer scheme, as shown in Fig. 1b, the transmitted light intensity is modulated by the applied voltage via electroabsorption, the photocurrent converted at the remote detector can be expressed as:

$$I_{trans} = \eta_d \Omega^2 T(V) P_{opt} \quad (4)$$

where η_d is the responsivity of the remote detector, Ω^2 is the total transmission factor of the EAD and the fiber, and $T(V)$ is the transfer function of the EAD normalized to the incident optical power. In (4), the photocurrent component corresponding to the mixing of ω_s and ω_{LO} is:

$$I_{trans}^{mix} = \frac{1}{2}\eta_d \Omega^2 T'(V_b) vp \cos(\omega_s \pm \omega_{LO})t \quad (5)$$

where $T'(V_b)$ is the first-order derivative of T evaluated at bias V_b.

3) Comparison of conversion loss of EAD detector /mixer and EAD modulator/mixer

The efficiency of frequency conversion of the above two schemes can be obtained from (3) and (5). The ratio R of the frequency-converted signal powers can be expressed as:

$$R(dB) = 20\text{Log}\left(\frac{I_{ph}^{mix}}{I_{trans}^{mix}}\right) = 20\text{Log}\left(\frac{I'_{ph}(V_b)}{I'_{trans}(V_b)}\right) \quad (6)$$

where I_{ph} and I_{trans} are the dc photocurrent detected at the EAD and the remote detector, respectively. The derivatives of the photocurrent are evaluated at the operating bias, V_b.

Typically, the responsivity of the remote detector η_d multiplied by the EAD transmission factor at the bias is less than the responsivity of the EAD, i.e., $\eta_d\Omega^2 T(V_b)<\eta(V_b)$. Therefore the detector/mixer has a smaller conversion loss.

2. Heterodyned modulator/mixer

Heterodyned modulator/mixer is designed to improve the efficiency of the conventional modulator/mixer. The optical LO is provided by two heterodyned lasers. In our scheme, only one of the laser beams goes through the EAD which is modulated by the RF signal (ω_s). The second laser beam is fed directly to the detector via the same fiber to provide the heterodyned reference for frequency conversion. This reference beam does not suffer the insertion loss through the EAD and, since the mixing depends on the product of optical intensities at the detector, the conversion efficiency is not limited by the optical saturation limit of the EAD. Moreover, this frequency translated optical link has the optical single-side-band transmission feature.

We analyze the conversion loss of the heterodyned modulator/mixer scheme by examining the optical spectrum and by applying the square law detection.

III. Conventional EAD Link with Single Laser

In Fig. 2, a conventional optical link is depicted in which the intensity modulation of the EAD creates two optical side bands symmetrically located around an optical carrier. Both side bands mix with the optical carrier at the detector to reproduce the original modulation signal.

At the square law detector, the detector photocurrent I_d of this link is expressed as [11]:

$$I_d(t) \propto \underline{2A^2 m_s \Omega_l^{\,2}} \cos[\frac{\theta(2\omega_s, L)}{2}]\cos[\omega_s t + \frac{\theta(2\omega_s, L)}{2}] + \cdots \quad (7)$$

$$\theta(2\omega_s, L) = \frac{1}{2\pi} DL \frac{\lambda^2}{c} \omega_s^2 \quad (8)$$

In (7) and (8), A is the optical carrier amplitude, m_s is proportional to modulation index. $\Omega_l^{\,2}$ is the link loss of optical signal, mostly due to the EAD insertion loss. The phase offset $\theta(2\omega_s,L)$ reflects the different group delay (i.e. the dispersion effect) of the two optical side bands through the fiber. D is the dispersion parameter, λ is the carrier wavelength, c is the free space speed of light. The dispersion induced RF power penalty of this single optical carrier link is $\cos^2[\theta(2\omega_s,L)/2]$, which limited the maximum transmission distance.

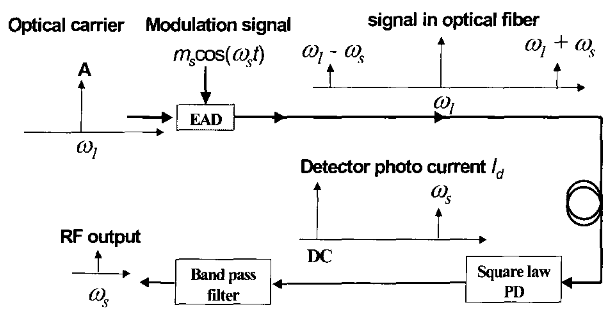


Fig. 2. Conventional RF fiber link with a single optical carrier

1. Conventional modulator/mixer with an optical LO

Fig. 3 shows a conventional modulator/mixer scheme where the optical LO is generated from two optical carriers phase locked to each other. Now, ω_s is an IF frequency; A' and B' are the amplitudes of each optical carrier, respectively. In order to compare this link with single carrier link, we assume the two EADs in Fig. 2 and Fig. 3 are identical, so they have same optical power handling. Therefore, same optical power is launched into the EAD ($A'^2+B'^2=A^2$). For the highest optical LO efficiency, modulation index of LO equals to one ($A'=B'=A/\sqrt{2}$). Under this situation, the detector photocurrent is expressed as:

$$I_d(t) \propto 2A^2 m_s \Omega_1^2 \cos[\frac{\theta(2\omega_s,L)}{2}]\cos[\omega_s t+\frac{\theta(2\omega_s,L)}{2}] \\ +A^2\cdot m_s\cdot\Omega_1^2 \cdot \begin{Bmatrix} \cos[\frac{\theta(2\omega_u,L)}{2}\frac{\omega_s}{\omega_u}]\cdot\cos[\omega_u t+\frac{\theta(2\omega_u,L)}{2}\frac{\omega_s}{\omega_u}] \\ +\cos[\frac{\theta(2\omega_L,L)}{2}\frac{\omega_s}{\omega_L}]\cdot\cos[\omega_L t+\frac{\theta(2\omega_L,L)}{2}\frac{\omega_s}{\omega_L}] \end{Bmatrix} \\ +\cdots \quad (9)$$

where $\omega_u=\omega_{LO}+\omega_s$ and $\omega_L=\omega_{LO}-\omega_s$ are up- and down-converted signals, respectively. Comparing (7) and (9), the dispersion effect in this scheme is reduced but the RF output power is 6 dB lower than that of the single laser link.

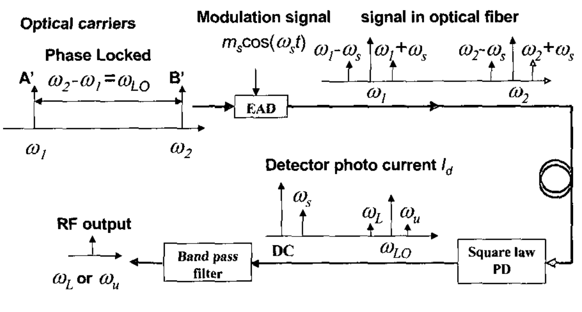


Fig. 3. Conventional modulator/mixer with an optical LO consisted of two phase-locked optical carriers.

IV. HETERODYNED MODULATOR/MIXER DESIGN

Fig. 4 shows the schematic diagram of our new approach. The optical LO is provided by two phase-locked optical carriers. One of them is coupled to the EAD, the modulated carrier is then combined with the other optical carrier. Fig. 4 also shows the spectra of the optical signal at the remote PD. At the PD, the two optical side bands mix with both optical carrier 1 (ω_1) and optical carrier 2 (ω_2). The former mixing process produces the IF electrical outputs. The latter mixing process produces the frequency converted signals (ω_u and ω_L). They can be separately filtered and detected. The detected RF signal from this optical heterodyned link does not suffer much from dispersion induced power penalty because of the single-side-band transmission.

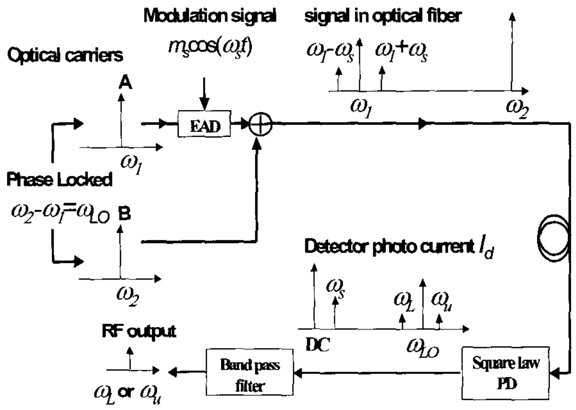


Fig. 4. Schematics of the heterodyned modulator/mixer.

In order to compare the conversion loss with the conventional modulator/mixer, the same optical power is coupled to the EAD. The detector current is expressed as:

$$I_d(t) \propto 2A^2\cdot m_s\cdot\Omega_1^2\cos[\frac{\theta(2\omega_s,L)}{2}]\cos[\omega_s t+\frac{\theta(2\omega_s,L)}{2}] \\ +A\cdot B\cdot m_s\cdot\Omega_1\cdot\Omega_2\{\cos[\omega_u t+\theta(\omega_u,L)] \\ +\cos[\omega_L t+\theta(\omega_L,L)]\}+\cdots \quad (10)$$

(9) and (10) indicate that the RF output power of heterodyned modulator/mixer is proportional to (msABΩ1Ω2)2 while that of a conventional modulator/ mixer is proportional to (msA2Ω12)2.

For our approach, optical carrier 2 bypasses the EAD so the link loss Ω2 includes only the fiber loss. Therefore, Ω2 is normally smaller than Ω1.

Furthermore, although the maximum power of optical carrier 1 is pinned by the optical saturation of the EAD, the power of optical carrier 2 can be increased to boost the output RF signal without considering the optical saturation of the EAD. The maximum power of carrier 2 is set by the detector saturation and the nonlinearity of the optical fiber.

The RF power is proportional to the square of the RF photocurrent of PD. Comparing the RF photocurrent in (9) with that in (10), the conversion gain enhancement factor φ is given by:

$$\varphi=\left(\frac{A\cdot B\cdot m_s\cdot\Omega_1\cdot\Omega_2}{A^2\cdot m_s\cdot\Omega_1^2}\right)^2=\frac{B^2\cdot\Omega_2^2}{A^2\cdot\Omega_1^2}=\frac{p_{2,d}}{p_{1,d}} \qquad (11)$$

where $P_{1,d}$ and $P_{2,d}$ are the respective powers of optical carrier 1 & 2 incident at the PD.

1. Reconfigurable RF optical link using both schemes

For certain applications, it would be desirable to have the flexibility of altering the center frequency of the signals. Fig. 5 shows a scheme for combining a heterodyned modulator/mixer at the transmitter end and a detector/mixer at the receiver end to achieve frequency agility. The frequency tuning signal, $v\cos(\omega_T t)$, mixes with the received signal via a detector/mixer. Referring to (3), the photocurrent includes the following components:

$$\begin{aligned}I_{ph}(V)\propto I_{ph}^{mix}+\tfrac{1}{4}A\cdot B\cdot m_s\cdot\Omega_1\cdot\Omega_2\cdot v\cdot\eta'(V_b)\\ \cdot\{\cos[(\underline{\omega_{LO}\pm\omega_T}+\omega_s)t+\theta(\omega_s+\omega_{LO},L)]\\ +\cos[(\underline{\omega_{LO}\pm\omega_T}-\omega_s)t+\theta(\omega_{LO}-\omega_s,L)]\}+\cdots\end{aligned} \qquad (12)$$

By varying ω_T, the RF central frequency can be shifted to different bands.

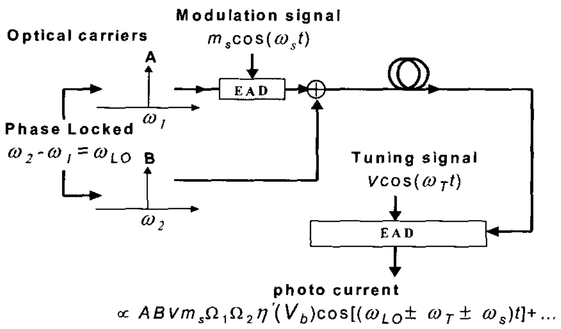


Fig. 5. RF transmission system using a modulator/mixer at the central office and a detector/mixer at the BS.

Replacing a regular photodiode with a detector/mixer can introduce some link gain penalty, which is expressed as:

$$10\log\left[\frac{1}{2}\frac{\eta'(V_b)}{\eta_d}v\right]^2 dB \qquad (13)$$

η and η_d are respectively the maximum responsivities of the EAD and the photodetector. For a typical case, where the EAD has a V_π of 1 V and η of 0.6mA/mW, and a η_d of 0.9mW/mA for the detector, and a tuning signal power of 2mW, the link gain penalty is about 14 dB.

V. EXPERIMENTS

1. Experiments of the Detector/mixer and the conventional modulator/mixer

We used an InAsP/GaInP strain-compensated MQW waveguide modulator EAD [12] in the work. The RF frequency conversion set up was shown in Fig. 6. Two Nd:YAG lasers generating a beat tone at 900 MHz with 100% modulation depth was used as an optical LO signal to the EAD mixer. An electrical voltage that has a dc bias superimposed on the RF signal at f_s = 1.0 GHz was applied to the EAD. The dc bias was –0.75 V, which corresponds to the highest slope efficiency of the photocurrent vs. bias curve of the EAD. An RF circulator (bandwidth 1-2 GHz) was inserted between the device under test and a RF spectrum analyzer was used to measure the RF power generated at the EAD. The transmitted power by the EAD was also observed at the RF spectrum analyzer after the PD.

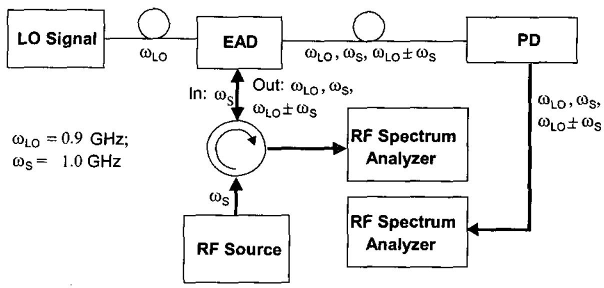
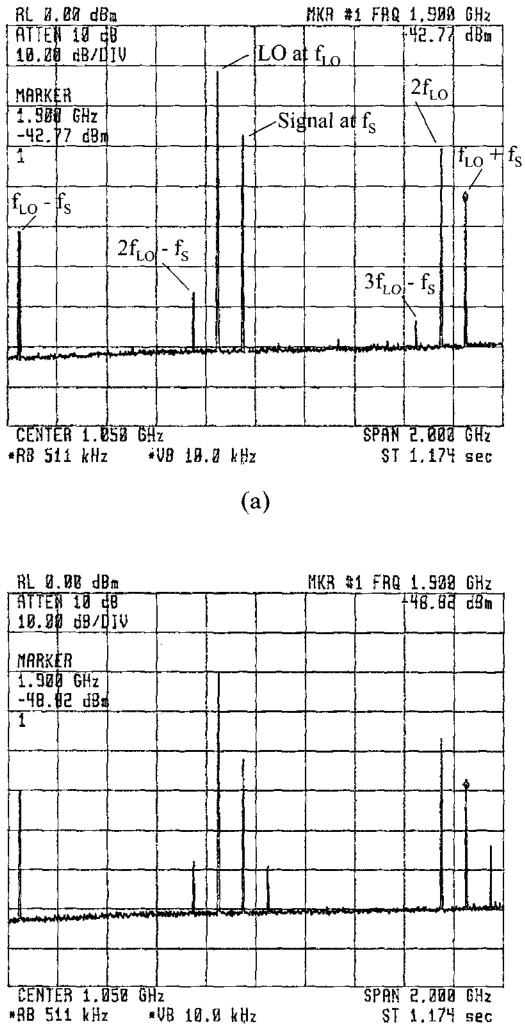


Fig. 6. Experimental setup for the frequency-conversion measurement using the EAD as a detector/mixer.

Fig. 7a summarizes the measured RF signals from the

MQW EAD. The optical LO power incident at the EAD was 10 mW and the input RF power was –20 dBm. The LO was observed at 900 MHz and the signal at 1.0 GHz. Up-converted signal power detected at 1.9 GHz was –38.9 dBm after accounting forth cable loss. When the RF signal power was increased to –10 dBm, the converted signal powers increased by 10 dB, in accordance with (3).



(b)

Fig. 7. Measured RF spectrum (a) at the MQW EAD, and (b) at the remote detector

Fig. 7b shows the RF power transmitted through the fiber and detected at the remote PD. It had a similar RF spectrum as in Fig. 7a, but due to the link loss, the original signal power at ω_s was attenuated (link loss = 21 dB). Up-converted signals were measured at –47.8 dBm after accounting for cable loss. The powers of the converted signals of this modulator/mixer are 6 dB less than that of IF signal, in agreement with(9). When the signal power is increased from –20 dBm to –10 dBm the converted signal powers is increased by 10 dB, as predicted by (5).

The conversion loss for the case when the EAD was used as a detector/mixer was measured at 18.9 dB. This loss was mainly limited by the LO optical power and the saturation power of the EAD used. When the same EAD was used as a conventional modulator/mixer, the conversion loss was increased to 27.8 dB. The increased conversion loss (8.9 dB) is in agreement with Eq.(6).

2. Experiment of heterodyned modulator/mixer:

In our heterodyned modulator/mixer experiment we directly measured the photocurrent enhancement factor δ_{ld} of the heterodyned link with respect to the conventional single carrier link. Recall that the RF power is proportional to the square of the RF photocurrent of PD, so in dB scale, the corresponding RF power gain improvement ϕ is twice of δ_{ld} . The conversion loss improvement is derived from RF gain enhancement. From(7), (9), (10) and(11), the conversion loss reduction φ is:

$$\varphi(dB) = \phi(dB) + 6dB = 2\delta_{ld}(dB) + 6dB \tag{14}$$

The additional 6 dB comes from the fact that we assumed the situation where $A' = B' = A/\sqrt{2}$.

The experimental setup is shown in Fig. 8, laser 1 and 2 are phase-locked. The beat tone of the two lasers is the optical LO set at 750 MHz. The 10 dB couplers tap 10% of the optical power from the two lasers and feed them to the laser controller. This is the feedback path for phase locking. The optical power from Laser 1 is attenuated below the saturation power of the EAD [12]. This carrier is modulated by a 0 dBm IF signal at 500MHz. After the EAD, the output from both beams are combined and examined using the light wave input of an RF spectrum analyzer, so the spectrum displayed is proportional to the detector photocurrent.

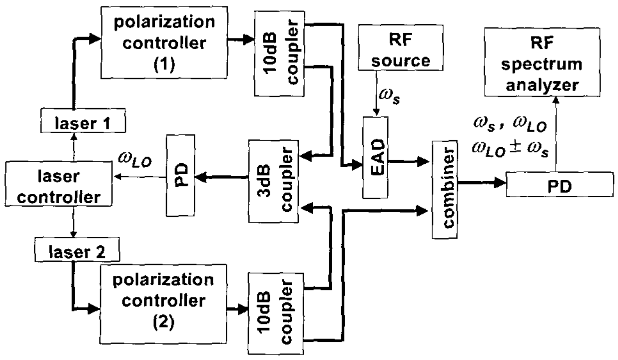


Fig. 8. The measurement set up of the heterodyned modulator/ mixer.

When laser 2 is off, the setup is identical to a single optical carrier link. The detector output spectrum is shown in Fig. 9. As expected, the output is a 500MHz signal, the same as the modulation signal applied to the EAD. This signal, as discussed earlier, is generated by two optical side band signals mixing with the optical carrier from laser 1. The $P_{1,d}$ is –23.1dBm (the AVG PWR value in the display).

Recall that $P_{1,d}$ ($P_{2,d}$) is the power of optical carrier 1 (2) incident at the PD [11].

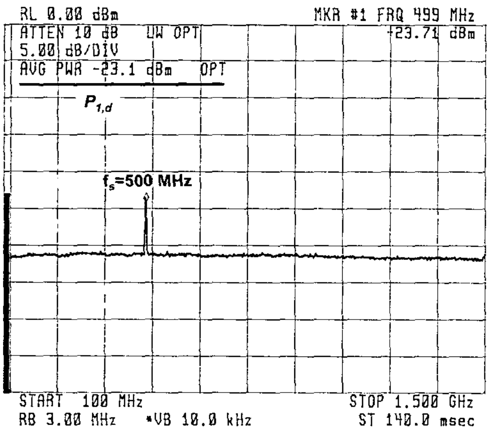


Fig. 9. The spectrum of the detector photocurrent of a single laser link.

When both lasers are on, the setup is a heterodyned modulator/mixer link. The output spectrum of the detector, as shown in Fig. 10, consists of the signal at 500MHz, the down-converted signal at 250MHz, the up-converted signal at 1.25GHz and the LO signal at 750MHz. Fig. 10 also shows the improvement of the RF output level of this heterodyned RF link. Here, the $P_{1,d}$ plus $P_{2,d}$ is –0.1dBm. This is the total average optical power of carrier 1 and 2 at the PD. Therefore, with $P_{1,d}$ at –23.1 dBm (Fig. 9), $P_{2,d}$ is calculated as -0.12 dBm. According to (11) and (14), the conversion loss enhancement φ is 23 dB and the RF power gain enhancement ϕ is 17 dB, the corresponding photocurrent gain enhancement δ_{Id} is 8.5 dB, which agrees very well with the measurement shown in Fig. 10.

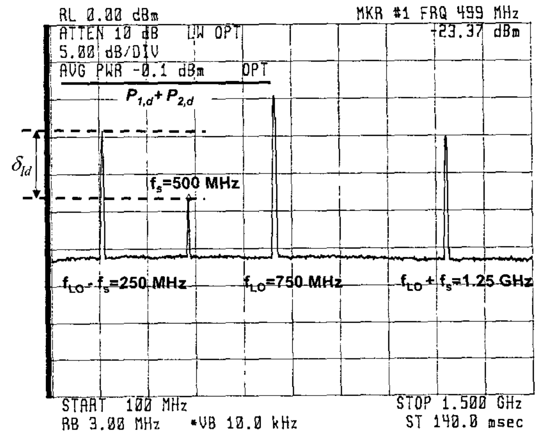


Fig. 10. The spectrum of the detector photocurrent of the single side-band heterodyned RF link.

From (11), we can see that the improvement is much influenced by the optical saturation power and the insertion loss of the EAD which are ~ 10 dBm and ~ 8 dB respectively for typical MQW EAM. Since the detector optical power handling can be as high as 20 dBm, the conversion loss improvement can reach 18 dB.

The large improvement comes from the the high loss and low optical power handling of the EAD. When the two parameters of the EAD are better, the conversion loss improvement brought by the heterodyned modulator/mixer will be less. The detector optical power handling can be as high as 20 dBm. It sets the upper limit of the conversion gain improvement for a given EAD. Currently, the optical saturation power and the insertion loss are ~ 10 dBm and ~ 8 dB respectively for typical MQW EAD. From Eq. (11), the conversion loss improvement can reach 18 dB.

VI. Conclusion

In summary, we presented the operating principle and experimental results of the EAD as an optoelectronic mixer. The detector/mixer shows a conversion loss less than that of a conventional modulator/mixer. A heterodyned modulator/mixer scheme is proposed to improve the conversion loss and is experimentally verified. Our scheme circumvents the insertion loss and the optical saturation of EAD. It also achieves single-side-band transmission, so the link is immune from dispersion induced power penalty. The two EAD mixer schemes can be combined to achieve RF link with agile center frequency.

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