

Tunable harmonic intensities with an electro-absorption modulator in a Sagnac fiber loop

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Tunable harmonic intensities based on an electro-absorption modulator (EAM) are presented. The configuration is based on a Sagnac loop interferometer containing an electro-absorption modulator (EAM). Signal responses are obtained by modulating the clockwise and counterclockwise propagating waves inside the Sagnac loop. Measured results verify the theoretical expressions and demonstrate continuously tunable ability of amplitude for fundamental and harmonic terms. Frequency doubled and tripled electrical signals are also demonstrated.

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1. Introduction

The analog optic link is a good interface between fiber-optical system and electronic system. The extremely low loss and wide bandwidth of the optical fiber enable us to distribute microwave signals from a centre control station to a number of remote stations. Therefore, it can be used for cable TV (CATV) network, antenna remoting and wireless communication systems [1-4]. The external modulation methods have many merits, such as low chirp and broadband operation compared to the direct modulation of laser diodes. Further, the Mach-Zehnder (MZ) intensity modulator can also provide functions as flexible harmonic generation and electrooptical upconversion by biasing the intensity MZ modulator. The doubled and tripled drive signal frequency generation is also important for optical analog link. Two times of the microwave drive signal frequency can be generated by carrier suppression with an MZ intensity [5]. The odd-order optical sideband suppression, together with an optical notch filter to filter out the optical carrier, to generate four times of the drive signal frequency is also reported with an optical MZ modulator [6]. Electro-absorption modulator (EAM) with low driving voltage operation, large bandwidth, polarization independent, and monolithic integration with a laser diode are expected to be useful in analog optical links compared with Mach-Zehnder (MZ) intensity modulator. However, the flexible harmonic intensities generation is difficult to achieve for EAM. The doubled and tripled frequency of the drive microwave signal is also difficult to be obtained with EAM.

In this paper, we demonstrate a new structure for RF signal generation and processing using a single electro-absorption modulator (EAM). It is based on a Sagnac loop interferometer formed by an EAM and a 3 dB 2×2 coupler. The tunable intensities of the fundamental and higher-order terms are obtained by modulating the clockwise and counterclockwise propagating waves inside the Sagnac loop at different time. Measured results verify the

theoretical expressions. The second-order harmonic suppression is achieved. By adjusting the polarization controller in the Sagnac loop, the two times and three times of the frequency of input RF signal is also obtained.

2. Experimental setup and operation principle

The schematic is shown in Fig. 1. Continuous wave from a DFB laser source is launched into the Sagnac loop through an isolator. The Sagnac loop consists of a 3 dB optical coupler, and an EAM which is located away from the loop centre and driven by an input RF signal.

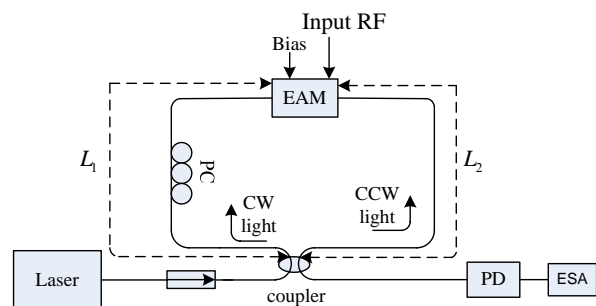


Fig.1. Experimental setup.

When light reaches the coupler, it is split into two equal parts. One half travels in the clockwise (CW) direction, passing through the EAM; the other half travels in the counter-clockwise (CCW) direction. A polarization controller (PC) introduces a variable phase difference between the CW and the CCW signals. The output modulated signal is detected by a photodetector (PD), which is followed by an electrical spectrum analyzer (ESA) to display the characteristic of output RF signal.

The transfer function of the EAM can be expressed by [7].

$$T(V) = P_{out}/P_{in} = \exp(-\alpha_1 V - \alpha_2 V^2) \quad (1)$$

where P_{in} is the optical input power, P_{out} is the output optical power, the linear term $\alpha_1 V$ comes from the Franz-Keldysh effect, the quadratic term $\alpha_2 V^2$ comes from the Quantum Confined Stark effect, $V = V_b [1 + m \cos(\omega_m t)]$ is the total voltage applied to the modulator, V_b is the bias voltage, and m is the RF modulating depth. Under only the the Franz-Keldysh effect [8], the amplitude transfer of the EAM can be expressed as

$$E(t) = \exp\left\{\frac{1}{2}\{-\alpha_1 V_b [1 + m \cos(\omega_m t)]\}\right\} \quad (2)$$

Thus the CW signal in the Sagnac loop, before exiting the coupler, can be expressed as

$$E_{cw}(t) = \frac{\sqrt{2}}{2} \sqrt{P_i} \exp(j\omega_0 t) \exp\left\{\frac{1}{2}\{-\alpha_1 V_b [1 + m \cos(\omega_m (t - T_1))]\}\right\} \quad (3)$$

where $T_1 = nL_2/c$, n is the fiber refractive index, ω_0 is the carrier frequency and c is the speed of light. The corresponding electrical field of the CCW light wave, before exiting the coupler, can be expressed as:

$$E_{ccw}(t) = \frac{\sqrt{2}}{2} \sqrt{P_i} \exp[j(\omega_0 t + \pi/2 + \phi)] \exp\left\{\frac{1}{2}\{-\alpha_1 V_b [1 + m \cos(\omega_m (t - T_1))]\}\right\} \quad (4)$$

where the phase shift of $\pi/2$ is due to the coupler, $T_1 = nL_1/c$, ϕ is phase difference between the CCW and CW signal. Then the output of the Sagnac loop can be written as

$$E(t) = \frac{\sqrt{2}}{2} \sqrt{P_i} \left\{ \begin{array}{l} \exp[j(\omega_0 t + \pi + \phi)] \exp\left\{\frac{1}{2}\{-\alpha_1 V_b [1 + m \cos(\omega_m (t - T_1))]\}\right\} \\ + \exp[j(\omega_0 t)] \exp\left\{\frac{1}{2}\{-\alpha_1 V_b [1 + m \cos(\omega_m (t - T_2))]\}\right\} \end{array} \right\} \quad (5)$$

By assuming the responsivity of the photodiode to be R , the output electrical current signal is given by

$$I(t) = \frac{RP_i \exp(-\alpha_1 V_b)}{2} \left\{ \begin{array}{l} \exp\{-\alpha_1 V_b m \cos[\omega_m (t - T_1)]\} \\ + \exp\{-\alpha_1 V_b m \cos[\omega_m (t - T_2)]\} \\ + 2 \cos(\pi + \phi) \exp\left\{-\frac{1}{2}\{-\alpha_1 V_b m \cos[\omega_m (t - T_1)]\}\right\} \\ - \frac{1}{2}\{-\alpha_1 V_b m \cos[\omega_m (t - T_2)]\} \end{array} \right\} \quad (6)$$

Using the Sonine expansions,

$$\exp(z \cos \beta) = J_0(z) + 2 \sum_{n=1}^{+\infty} J_n(z) \cos(n\beta) \quad (7)$$

the Eq.(6) can be represented as

$$I(t) = RP_i \exp(-\alpha_1 V_b) \left\{ \begin{array}{l} J_0(a) + \cos(\pi + \phi) J_0(ab) + J_1(a) \{\cos[\omega_m (t - T_1)] + \cos[\omega_m (t - T_2)]\} \\ + 2 \cos(\pi + \phi) J_1(ab) \cos[\omega_m (t - T)] \\ + J_2(a) \{\cos[2[\omega_m (t - T_1)]] + \cos[2[\omega_m (t - T_2)]]\} \\ + 2 \cos(\pi + \phi) J_2(ab) \cos[2\omega_m (t - T)] \\ + J_3(a) \{\cos[3[\omega_m (t - T_1)]] + \cos[3[\omega_m (t - T_2)]]\} \\ + 2 \cos(\pi + \phi) J_3(ab) \cos[3\omega_m (t - T)] + \dots \end{array} \right\} \quad (8)$$

Where $a = -\alpha_1 V_b m$, $b = \cos[\phi]$, $\phi = \omega_m \left(\frac{T_2 - T_1}{2}\right)$,

$T = \frac{T_2 + T_1}{2}$. After rearrangement, Eq.(8) becomes

$$I(t) = RP_i \exp(-\alpha_1 V_b) \left\{ \begin{array}{l} J_0(a) + \cos(\pi + \phi) J_0(ab) \\ + [2 \cos(\pi + \phi) J_1(ab) + 2 J_1(a) \cos(\phi)] \cdot \cos[\omega_m (t - T)] \\ + [2 \cos(\pi + \phi) J_2(ab) + 2 J_2(a) \cos(2\phi)] \cdot \cos[2\omega_m (t - T)] \\ + [2 \cos(\pi + \phi) J_3(ab) + 2 J_3(a) \cos(3\phi)] \cdot \cos[3\omega_m (t - T)] + \dots \end{array} \right\} \quad (9)$$

Eq.(9) clearly shows that the amplitude for the fundamentals and harmonic terms are dependent on the ϕ and ϕ . Since ϕ is the phase difference between CCW and CW signal in the Sagnac loop, by tuning the polarization controller in the Sagnac loop, the amplitude of the fundamental and higher-order harmonic terms will be adjusted.

3. Experimental results and discussion

The operation of the tunability of the harmonic intensities, and generation doubled and tripled drive signal frequency have been verified by experiments. The DFB laser (AQ2200-111) source has a linewidth of 100 kHz, and the input 6 GHz RF signal power is 16 dBm. The EAM module is OKI OM5642W-30B. The measured curve for transmitted optical power as a function of the modulator reverse bias is shown in Fig. 2. The operation bias is -1.15 V to get transmission ratio value of 0.5. In the experiment, the path difference $L_2 - L_1$ for the EAM location in the Sagnac loop is 14.3 cm.

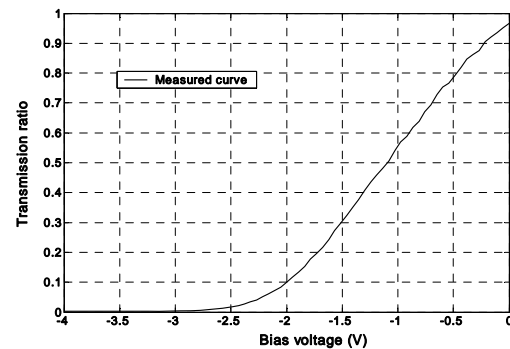


Fig. 2. The measured EAM transmitting ratio as a function of the modulator reverse bias.

With the adjustments of the PC in the Sagnac loop, power equalized fundamental and second-order harmonics

is achieved. The measured optical spectrum of the transmitted signal is shown in Fig. 3. The output RF power for fundamental harmonic is almost the same as the second-order harmonic.

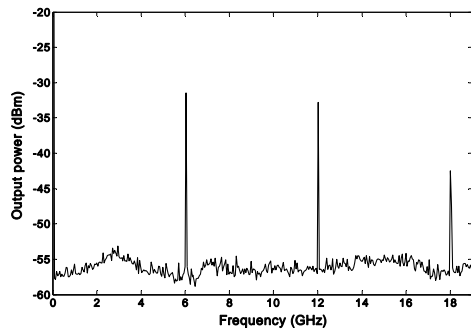


Fig. 3. Equalized fundamental and second-order harmonic generation.

The harmonics may fall in-band and cause distortion, especially for the second-order harmonic whose intensity is much higher than other higher-order harmonic. So, it is important to suppress the second-order harmonic. Fig. 4 clearly shows second-order harmonic suppression, with more than 25 dB suppression through adjusting the PC.

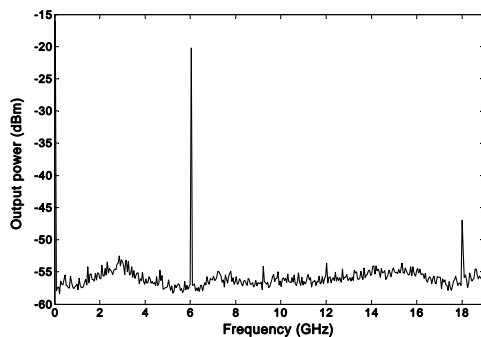


Fig. 4. Second-order harmonic suppression generation.

Double and triple times the frequency of the microwave drive signal is difficult to be achieved in electrical domain. Hence all-optical generation and processing of the two and three times the frequency of the microwave drive signal is very attractive for the EAM. By adjusting the PC in the Sagnac loop, the amplitude of fundamental harmonic can be consciously reduced to achieve the pure two and three times the frequency of the 6 GHz input RF signal. Fig. 5 clearly shows the high quality 12 GHz and 18 GHz RF signal generation.

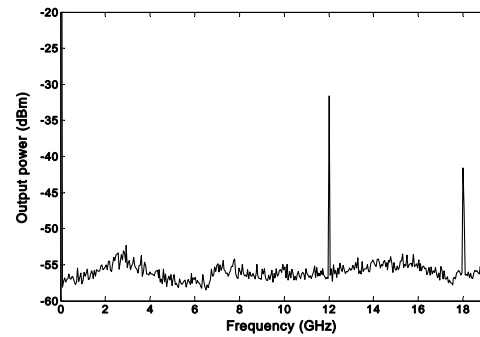


Fig. 5. Two and three times of the frequency of the input microwave signal generation.

4. Conclusions

We have demonstrated a new structure for tunable amplitudes of harmonics. It is based on a Sagnac loop interferometer formed by an electro-absorption modulator and a 3 dB 2×2 coupler. The tunable amplitudes of the fundamental and higher-order terms are obtained by modulating the clockwise and counterclockwise propagating waves inside the Sagnac loop at different time. Measured results verify the theoretical expressions. By adjusting the polarization controller in the Sagnac loop, the two times and three times of input RF signal frequency as well as the second-order harmonic suppression are achieved.

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