All Optical Microwave Frequency Division by 2^n

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Abstract—This paper presents the concept and analysis of an all optical divide-by-2^n microwave frequency divider. It uses a Mach-Zehnder light intensity modulator with 100% modulation IM index which is utilized to generate a subharmonic optical sideband. This optical sideband when mixed with the optical carrier in a photodiode produces a difference frequency signal which is a sub-harmonic (divided-by-2) of the primary modulation frequency. This all optical circuit is simple, novel and low noise in character.

Microwave signal frequency division [1-9] finds applications in many areas of communication. It is used in microwave frequency synthesis. It can be used in microwave sub-harmonic generation. Microwave frequency division is used in laboratory electronic instruments. This microwave frequency division requires no local oscillator which is normally used in down conversion.

In microwave measurement system and in radar, frequency translation is required in which case frequency division can be applied. In microwave phase lock loops frequency division is used. In frequency division multiplexing, microwave frequency dividers can replace the need for highly stable, coherent carrier generation. Multiple carriers can be generated for radio communication by using microwave frequency dividers. Clock frequency division by the factor 2^n can be achieved by using microwave frequency dividers.

In this paper, we propose and analyze a novel all optical circuit for microwave frequency division by the factor 2^n which uses external intensity modulation of a DFB laser in each stage. The most important feature of this frequency divider is that it is a low noise device since it utilizes the technique of optical injection locking [10, 11] and optical injection locking can reduce input signal relative intensity noise (RIN) [12-17] by several order in magnitude with a high power gain.

To design an all optical microwave frequency divider, we take a DFB LD lasing at 1.55µm, the corresponding radian frequency being ω_c. Its output power, P_0, is divided into two halves, each of power $P_0/2$, in a half mirror (HM). One of the two light waves reflected by a full mirror (FM), is injected into another DFB LD (ILLD2) lasing at radian frequency ω_c under free-running condition. The laser diode ILLD2 falls in synchronism with the injection signal at the radian frequency ω_c. The output of the locked LD is reflected by a full mirror (FM) and fed to the second input of the (2×1) optical combiner.

The other light wave half-power divided by the HM is intensity modulated in a Mach-Zehnder intensity modulator (MZIM), driven by the microwave signal of radian frequency ω_m, which is to be divided.

The modulator is under-driven with a microwave voltage amplitude (v_{m0}) of v_π/π where v_π is the half-wave voltage of the modulator. The intensity modulation index of the IM light wave at the output of the MZIM is $m=(\pi v_{m0}/v_\pi)$ which is taken as unity.

The frequency components present at the output of the modulator are $(\omega_c+\omega_m/2)$ and $(\omega_c-\omega_m/2)$ which are demultiplexed by an arrayed waveguide grating (AWG). The light wave with frequency $(\omega_c+\omega_m/2)$ is selected and injected into a DFB LD (ILLD1) lasing at the same frequency under free-running condition. The injection locked ILLD1 output is fed to the first input of the (2×1) optical combiner. The combined light wave pair is fed to the input of the photodiode. The photodiode develops an output current proportional to the input optical power and a voltage is developed at the detector load. The microwave signal frequency is divided by 2 and the subharmonic signal is displayed in the microwave spectrum analyzer.

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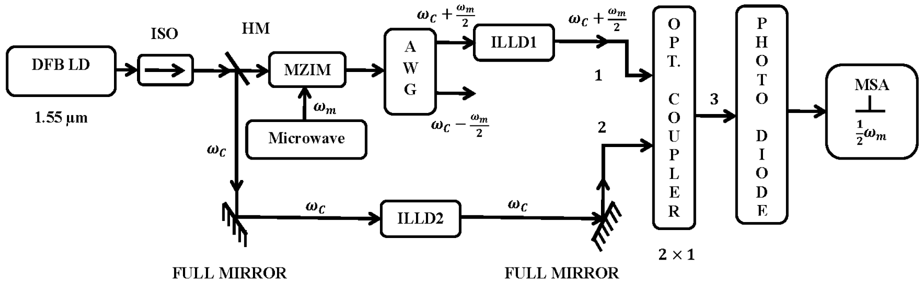

Fig. 1. Schematic circuit diagram of the divide-by-2 microwave frequency divider. ISO: Isolator; MZIM: Mach-Zehnder light intensity modulator; AWG: arrayed waveguide grating; ILLD: injection locked laser diode; MSA: microwave spectrum analyzer; HM: half mirror.

Let P_0 be the output power of the input DFB LD. The electric field of the lightwave output from this LD can be expressed as

$$E_c(t) = \sqrt{P_0}\cos\omega_c t, \tag{1}$$

where ω_c is the radian frequency of the light wave. The injected light wave into ILLD2 is given by

$$E_{inj}(t) = \sqrt{\frac{P_0}{2}}\sin\omega_c t. \tag{2}$$

The output light wave from the injection-locked laser diode [10-11] ILLD2 is written as

$$E_2(t) = \sqrt{P_L}\sin\omega_c t, \tag{3}$$

where P_L is the free-running power of ILLD2. Here, we have assumed that $(P_0/2) \ll P_L$ so that the injection level is low and the locked LD power is almost equal to the free-running power.
The microwave modulating signal voltage is written as

$$v_m(t) = v_{m0}\sin\omega_m t, \tag{4}$$

where v_{m0} is the voltage amplitude and ω_m is the radian frequency of this signal. The power modulation at the output of the MZIM is expressed as

$$P(t) = \frac{P_0}{2}\left(1 + m\sin\omega_m t\right), \tag{5}$$

where $m=(\pi v_{m0}/v_\pi)$ is the power modulation index and v_π is the half-wave voltage of the modulator. We take $v_{m0}=v_\pi/\pi$ so that $m=1$. The electric field of the light wave output from the modulator is written as

$$\begin{aligned} E_{\mathrm{mod}}(t) &= \sqrt{P(t)}\cos\omega_c t = \\ &= \sqrt{\frac{P_0}{2}}\left(\sin\frac{\omega_m t}{2} + \cos\frac{\omega_m t}{2}\right)\cos\omega_c t = \\ &= \frac{1}{2}\sqrt{P_0}\left[\sin\left\{\left(\omega_c + \frac{\omega_m}{2}\right)t + \frac{\pi}{4}\right\} - \sin\left\{\left(\omega_c - \frac{\omega_m}{2}\right)t - \frac{\pi}{4}\right\}\right]. \end{aligned} \tag{6}$$

The AWG splits the two optical frequency components $(\omega_c+\omega_m/2)$ and $(\omega_c-\omega_m/2)$. We select $(\omega_c+\omega_m/2)$ frequency component and inject into the ILLD1 which lases at $(\omega_c+\omega_m/2)$ radian frequency under its free-running condition. The output of ILLD1 is then

$$E_1(t) = \sqrt{P_L}\sin\left\{\left(\omega_c + \frac{\omega_m}{2}\right)t + \frac{\pi}{4}\right\}, \tag{7}$$

where P_L is the locked laser power which is nearly the same as the free-running output power under low-level injection. ILLD1 and ILLD2 are assumed to have identical power.
The resultant light wave at the input of the photodiode (PD) is

$$\begin{aligned} E_R(t) &= E_1(t) + E_2(t) = \\ &= \sqrt{P_L}\left[\sin\left\{\left(\omega_c + \frac{\omega_m}{2}\right)t + \frac{\pi}{4}\right\} + \sin\omega_c t\right]. \end{aligned} \tag{8}$$

The PD input optical power is

$$P_D\big|_{in} = \left|E_R(t)\right|^2 = P_L\left[1 + \cos\left\{\frac{\omega_m t}{2} + \frac{\pi}{4}\right\}\right]. \tag{9}$$

The $2\omega_c$ component is filtered out. The microwave voltage developed at the output of the PD is calculated as

$$v_0(t) = \eta P_L R_L \cos\left\{\frac{\omega_m t}{2} + \frac{\pi}{4}\right\}, \tag{10}$$

where R_L is the PD load resistance and η is the responsivity of the PD. The subharmonic power at $\omega_m/2$ radian frequency is calculated as

$$P_{SH} = \frac{1}{2}\eta^2 P_L^2 R_L. \tag{11}$$

In experiment, η=0.88mA/mW and R_L=50Ω. Taking P_L=20mW, we get P_{SH}=7.7mW. The variation of subharmonic power as a function of ILLD power is shown in Fig. 2 which shows a parabolic nature.
A microwave frequency divider by the factor 2^n (for n = 1, 2, 3,…) can be designed by cascading n number of primary stage of divide-by-2 frequency divider. In this case, the output signal of frequency $\omega_m/2$ of the first stage is used as the modulator drive signal of the second stage which produces a signal output at frequency $\omega_m/4$.

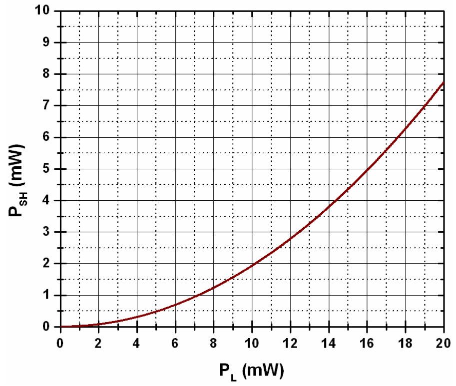

Fig. 2. Variation of subharmonic power (P_{SH}) as a function of ILLD power (P_L).

This cascaded frequency divider which produces frequency division by the factor 2^n (n = 1, 2, 3…) is shown schematically in Fig. 3. This principle of frequency division can be applied to mm-wave signals as well.

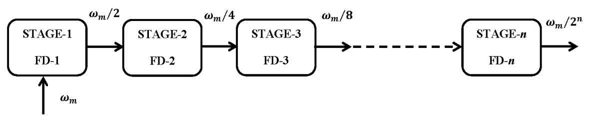

Fig. 3. Cascaded microwave frequency divider – divide-by-2^n; (n = 1, 2, 3…). FD-n: n-th stage frequency divider.

In this paper, we have proposed and analyzed the performance of an all optical microwave frequency divider using external intensity modulation of a DFB laser diode. The output sub-harmonic power follows a square law dependence on the injection-locked laser power. This frequency divider is a low noise type since the injection-locked laser diode suppresses laser relative intensity noise (RIN) by several order in magnitude. Finally, this circuit provides a stable, low noise, coherent microwave signal source which can act as a frequency reference.

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