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Optical microwave generation using modified sideband injection synchronization with wide line-width lasers for broadband communications

A. Banerjee[a,*], N.R. Das[b], B.N. Biswas[c]

[a] Department of Applied Electronics and Instrumentation Engineering, Academy of Technology, Adisaptagram, Hooghly 712121, West Bengal, India
[b] Institute of Radio Physics and Electronics, University of Calcutta, 92 A.P.C. Road, Kolkatta 700009, India
[c] Education Division, SKF Group of Institution, Sir J. C. Bose School of Engineering, Mankundu, Hooghly 712139, West Bengal, India

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ABSTRACT

In future generation space based phased arrays and in pico-cellular broadband mobile communication systems operating at microwave frequencies optical techniques for transport and generation of electrical signals are widely used. In general, there are two main classes of optical transmitting and generating microwave frequencies: (1) methods using direct or external intensity modulation of lasers and (2) heterodyning method using two coherent optical waves. The present paper dwells on the second method. The present paper overcomes the major practical limitations of optical sideband injection locking. Simulation results have been given in support of the analytical result.

1. Introduction

In creasing demand for broadband mobile communication and limited atmospheric propagation at mm-waves has resulted in the need for high density pico-cells. And as such future cellular broadband mobile communication systems will comprise mm-wave components for radio link between the mobile station (MS) and the numerous base stations (BS), which are remotely controlled by the central station (CS). Moreover, the base stations are widely separated from the central station, optical transport of the mm-wave signal is the choice owing to the inherent low transmission loss coefficient of the optical fibers. This, in turn, requires the use of lasers and photo-detectors. The cost of numerous BS's should be kept as low as possible. Therefore, generation and control of mm-wave signals should be optically carried out at the control station [1–5], making use of the proposed optical devices needed for the purpose of transport of the mm-wave signals. This avoids the need for mm-wave oscillators and modulators in the numerous base stations. In achieving this purpose two approaches are adopted, viz., (1) single optical source technique and (2) multiple optical source technique.

The single optical source technique is the simplest approach for impressing microwave signal on an optical carrier. It can be realized either by direct current modulation of semiconductor laser or with an electro-optic modulator (Mach Zehnder Modulator (MZM)). Direct current modulation is limited to frequency range below 15.0 GHz and accompanied by a large microwave noise floor due to laser intensity noise RIN and large harmonic content due to laser diode non-linearity. Another disadvantage is non-flat frequency response. Although indirect intensity modulation method MZM enjoys the advantage of large bandwidth over the direct modulation scheme, it suffers from non-linear response, limited modulation depth, optical insertion loss, cost and complexity.

At frequencies, above which direct modulation or external modulation has the limitation, one method [1,6], of accomplishing optical generation of electrical signal is obtained by mixing the outputs from two very narrow line-width lasers. But it is not commercially viable because of prohibited costs. Use of commercially available DFB lasers, although eliminates the cost, ends up with the generation electrical signal with large line-width due to inherent laser phase noise of the each source. The spectral purity of the electrical signal can be improved if the noise terms of the optical waves are correlated. The easiest way of to achieve this is to utilize the technique of sideband injection locking of two commercial laser diodes with line-widths in range of few megahertz. The master laser is frequency modulated to create sidebands in the laser optical spectrum. The slave lasers are synchronized to sideband components of the FM signal. The important point is that two slave lasers,

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[*] Corresponding author.
E-mail addresses: abhb7887@yahoo.in (A. Banerjee), nrd@ieee.org (N.R. Das), b.baidyanath@yahoo.com (B.N. Biswas).

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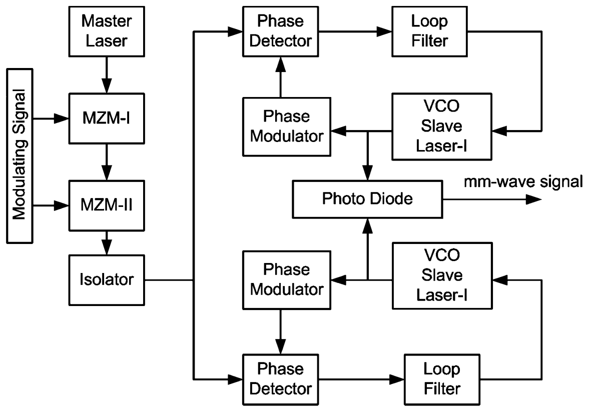

Fig. 1. Block schematic of proposed modified optical phase locking arrangement.

used as active high-Q circuits [7], are thus phase coherent with the master laser and each other, while their frequency separation equals the integer multiples of master laser frequency modulation. The main practical limitations are: (1) the locking range is small (typically a few hundred MHz) so that the laser temperature must be controlled with milli-kelvin precision, as the temperature sensitivity is typically 1.0 GHz/°K and (2) the disturbing effect of pulling and pushing effects due to the neighboring sidebands, and the deleterious effect of loop propagation delay. In this paper, we present a modified optical phase locking techniques which is shown in Fig. 1. This modified optical phase locking system overcomes the major practical limitations of optical sideband injection locking.

2. System description

Fig. 1 comprises three basic arrangements, viz., (i) sideband generation scheme, (ii) arrangement for phase locking with an additional phase modulator, and (iii) heterodyning of two outputs of the modified optical phase lock system at the photo-detector to generate the millimeter wave signal. The master laser is intensity modulated in such a way as to generate only two required sidebands as far as practicable in order to lock the two slave lasers to the sidebands without interference from the adjacent sideband components. The important point is that the two slave lasers, used as active high-Q circuits, are thus phase coherent with the master laser and each other, while their frequency separation equals the integer multiples of master laser frequency modulation.

Let the input to the cascaded MZ modulator be $E_m\cos(\omega_i t+\alpha(t))$, where $\alpha(t)$ is the phase noise of the master laser and E_m is the field associated with the master laser. Assuming the applied modulating voltages (drive voltage) to the two MZMs as

$$v_1 = \left({}^{V_\pi}\!/\!_2\right) + xV_\pi \sin(\omega t) \tag{1}$$

$$v_2 = \left({}^{3V_\pi}\!/\!_2\right) + xV_\pi \sin(\omega t) \tag{2}$$

where xV_π is the normalized amplitude of the modulating signal.

Noting that the transfer function of an MZM as $T = {}^1\!/\!_2\left[1+\sin\left(\pi{}^{v}\!/\!_{V_\pi}\right)\right]$, it is not difficult to show that the transfer function of the two-cascaded MZM is

$T = {}^1\!/\!_4\left[1-\cos^2\left(\pi{}^{v}\!/\!_{V_\pi}\right)\right] = {}^1\!/\!_4\sin^2(x\pi\sin(\omega t))$, where v is the input drive voltage and V_π is the half-wave voltage. Therefore, the output optical field of the modulator is given by $E_i(t) = {}^1\!/\!_2 E_I\sin(x\pi\sin(\omega t))\cos(\omega_i t+\alpha(t))$. That is,

$$E_i(t) = E_I\left\{\begin{array}{l} J_1(x)\sin\left[(\omega_i\pm\omega)t+\alpha(t)\right]+J_3(x)\sin\left[(\omega_i\pm3\omega)t+\alpha(t)\right]+ \\ J_5(x)\sin\left[(\omega_i\pm5\omega)t+\alpha(t)\right]+\cdots \end{array}\right\} \tag{3}$$

where ω_i is the incoming optical signal frequency.

Let the modulation bandwidth of the master laser is close to 10.0 GHz, and it is desired to generate 60.0 GHz mm-wave signal. Using the drive voltages with $x\pi = 3.843$, the modulator output can be approximately written as

$$\begin{aligned} E_i(t) = E_I\,\{&0.43\sin\left[(\omega_i\pm3\omega)t+\alpha(t)\right] \\ &+0.114\sin\left[(\omega_i\pm5\omega)t+\alpha(t)\right]\} \end{aligned} \tag{4}$$

The third harmonic components have been picked up, because the output mm-wave signal is required to be of 60.0 GHz with modulating frequency of 10.0 GHz. Disturbing components are away by 20.0 GHz and 6.0 dB less in amplitude causing almost no pulling and pushing force on the slave laser.

3. Governing equation of the system

In the following, for the sake of simplicity, we assume that the two modified OPLL (as shown in Fig. 1) are identical. Let the output of the laser VCO after the phase modulator be

$$E_0 = \cos[\omega_{01}t + \Psi_{VCO}(t) + \Psi_{PM}(t) + \beta_1(t)] \tag{5}$$

where ω_{01} is the free running frequency of the slave laser VCO, $\beta_1(t)$ is the phase noise of the slave laser, $\Psi_{VCO}(t)$ is the phase modulation produced due to the laser VCO frequency modulation and $\Psi_{VCO}(t)$ is given by

$$\psi_{VCO}(t) = 2\pi k\int_{-\infty}^{t} V_f\left(t'-\tau\right)dt' \tag{6}$$

where $V_f(t)$ is the loop filter output signal, k is the VCO laser sensitivity in Hz/V and τ is the loop propagation delay. In (5), $\Psi_{PM}(t)$ is phase modulation due to the phase modulator at the output of the laser VCO and is given by

$$\psi_{PM}(t) = k_P V_f(t-\tau) \tag{7}$$

where k_p is the phase modulator sensitivity in rad/V.

Assuming a balanced optical phase detector and neglecting shot noise, it is easily shown that the photo-detector output is given by

$$V_\phi(t) = A\sin\phi(t) \tag{8}$$

with $A = 2.r.R.\sqrt{P_r P_0}$ and $\phi(t) = \Omega t - \psi_{PM}(t) - \psi_{VCO}(t) + \left(\alpha-\beta_1\right)$, where Ω is the open-loop frequency error.

Let the filter be used an integrating one (active low pass filter) with transfer function $F(s) = {}^{(1+s\tau_2)}\!/\!_{s\tau_1}$. If its output is $V_f(t)$, then it is related to its input, $V_\phi(t)$, by the following equation:

$$\tau_1\frac{dV_f(t)}{dt} = \tau_2\frac{dV_\phi(t)}{dt} + V_\phi(t) \tag{9}$$

where τ_1 and τ_2 are the filter time constants.

Now, the active LPF output can be expressed by

$$V_f(t+\Delta t) = V_f(t) + V_\phi(t).\left[\frac{\Delta t-\tau_2}{\tau_1}\right] + \frac{\tau_2}{\tau_1}.V_\phi(t+\Delta t) \tag{10}$$

where Δt is the sampling interval, $V_f(t)$ and $V_f(t+\Delta t)$ are the loop filter output at t-th and $(t+\Delta t)$-th instant of time, respectively, $V_\phi(t)$ and $V_\phi(t+\Delta t)$ are the balanced phase detector output at t-th and $(t+\Delta t)$-th instant of time, respectively.