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Optical Heterodyning of Injection-Locked Laser Sources — A Novel Technique for Millimeter-Wave Signal Generation

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***Abstract*—**A novel technique has been developed to generate ultra-stable millimeter-wave signal by optical heterodyning of the output from two slave laser (SL) sources injection-locked to the sidebands of a frequency modulated (FM) master laser (ML). Precise thermal tuning of the SL sources is required to lock the particular slave laser frequency to the desired FM sidebands of the ML. The output signals from the injection-locked SL when coherently heterodyned in a fast response photo detector like high electron mobility transistor (HEMT), extremely stable millimeter-wave signal having very narrow line width can be generated. The scheme may also be used to generate ultra-stable sub-millimeter-wave/terahertz signal.

***Keywords*—**FM sideband injection locking, Master-Slave injection locking, Millimetre-wave signal generation and Optical heterodyning.

I. Introduction

STRINGENT requirements from various emerging applications like broadband wireless access network for pico-cell mobile communication, software-defined radio, space-based phased array antenna etc. demand optical technique for generation of millimeter-wave/terahertz signals. The primary advantage of signal generation by optical technique, i.e. by optical heterodyning of laser signals, is the possibility of realizing low phase-noise (i.e. small time jitter) of the generated millimeter-wave/terahertz signal. In general, laser sources are coherent sources but two different laser sources will not be mutually coherent. Thus if two different laser sources are heterodyned then there is no phase correlation between the mixing waves, and hence the overall phase noise of the difference frequency signal will be the sum of the phase noise of the mixing waves. However, if we heterodyne two phase-coherent signals in a non-linear device then the effective phase-noise of the difference signal happens to be equal to the difference of the phase-noise of the two individual beating signals [1]. We have used this principle to generate ultra-stable i.e. low phase-noise millimeter-wave signal. The scheme consists of a mode-locked master laser and two slave lasers which are injection-locked to the desired FM sidebands of the frequency modulated master laser, as shown in Fig. 1. The signals from the two injection-locked slave lasers are then heterodyned in a fast response photo detector (PD), which in our case is a HEMT device, that is followed by a suitable filter (not shown in the figure) to select out the desired beat (i.e. the difference) frequency as millimeter-wave signal. As indicated in the figure, the scheme may as well be realized if the two FM sidebands of the modulated master laser after being processed through optical phase-lock loops (OPLL) are heterodyned in the photo detector to produce the millimeter-wave signal.

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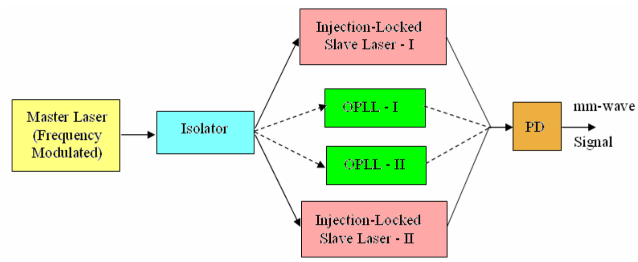

Fig. 1 The scheme for generation of ultra-stable millimeter-wave signal

II. Analytical Basis of the Scheme

To accomplish FM sideband injection locking, the master laser (ML) is frequency modulated (FM) by a RF signal at a frequency, f_m. The field amplitude E(t) of the FM modulated ML output is given by:

$$E(t) = E_0 e^{j\{2\pi f_0 t + \beta \cos(2\pi f_m t) + \varphi(t)\}} \tag{1}$$

where φ(t) represents the random phase fluctuations of the optical carrier. $\beta = f_d/f_m$ is the modulation index (f_d being the maximum frequency deviation) and f_0 is the master laser frequency with no modulation. The optical frequency of slave laser I can be adjusted by varying its heat-sink temperature (thermal tuning) and DC drive current so that it coincides with the +2 sideband of the ML at ($f_0 + 2f_m$), while the output frequency of slave laser II is accordingly made to coincide with the – 2 sideband of the ML at ($f_0 - 2f_m$). Decomposing the FM portion of (1) into its Fourier components we have:

$$E(t) \propto \left[\sum_{n=-\infty}^{n=+\infty} J_n(\beta) e^{j2\pi(f_0 + nf_m)t} \right] e^{j\varphi(t)} \tag{2}$$

where Jn are the Bessel functions of first kind, of order n. The power spectrum of (2) is given by [2]:

$$S(t) \propto \left[\sum_{n=-\infty}^{n=+\infty} \delta(f_0 + nf_m) \right] * S_l(v) \quad (3)$$

where * indicates convolution, and $S_l(v)$ represents the Lorentzian spectral line shape of the laser emission.

When slave laser I and slave laser II are injection-locked to the n = K and n = M sidebands, they suppress [3] all but that sideband, when locking half-bandwidth $v_l/2 << f_m$, and their emission fields are, respectively, given by:

$$E_1(t) \propto e^{j[2\pi(f_0+Kf_m)t+\varphi(t)]}$$
$$E_2(t) \propto e^{j[2\pi(f_0+Mf_m)t+\varphi(t)]} \quad (4)$$

Using the above two equations given by (4) in the expression for photo detector current: $i(t) \propto |E_1 - E_2|^2$, the beat-frequency signal at the output of the photo detector is given by:

$$i(t) = V[P_1 - P_2 + 2\sqrt{P_1 P_2}\cos(K-M)2\pi f_m t)] \quad (5)$$

where V is the photo detector responsively, P_1 and P_2 are the power incident on the photo detector from slave laser I and slave laser II, respectively.

The beat-frequency signal at the locked condition of the slave laser signal with FM side bands of the ML will have very narrow Full Width at Half Maxima (FWHM) line width [4] as a consequence of the high degree of coherence of the two injection-locked signals from the two slave laser sources. The frequency stability of the RF oscillator modulating the ML must be extremely good otherwise, even under locked condition, a slight jitter may occur in the beat-frequency signal.

III. Characterization Results and Discussion

The master laser source is at 600 THz which is frequency modulated with a base band signal of 15 GHz. The FM spectrum of the modulated master laser is shown in Fig. 2, where we have taken β = 1.35. The plot in Fig. 2 has been obtained by taking n-point ($n = 2f_c/f_m$) Fast Fourier Transform of y(t), where:

$$y(t) = \cos(2\pi f_0 t + \beta \sin 2\pi f_m t) \quad (6)$$

Next we carried out software simulation study for the frequency change of slave laser frequency with change in temperature to which the slave laser cavity is subjected to. The model equation for this is given by [5]:

$$\Delta f = n\frac{c}{2\eta(L + \alpha L \Delta T)} - f \quad (7)$$

where L is the length of the cavity, η and α are respectively the refractive index and the temperature coefficient of the material of the cavity and n is the mode number. The frequency change of the slave laser signal with change in temperature of the slave laser cavity for different materials is shown in Fig. 3 (a). For a typical frequency change equal to twice the modulation frequency ($2f_m$) corresponding to the second sideband of the FM output of ML for quartz cavity used for slave laser is shown in Fig. 3 (b).

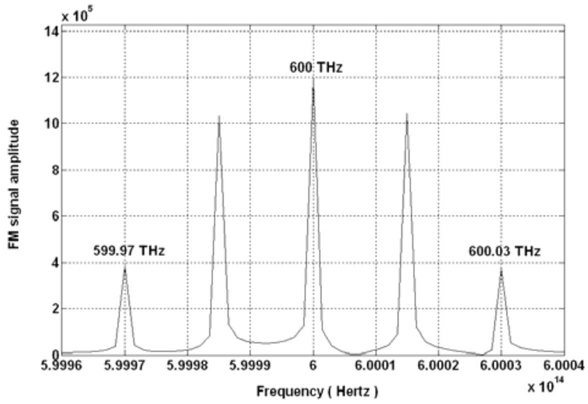

Fig. 2 FM spectrum of modulated master laser

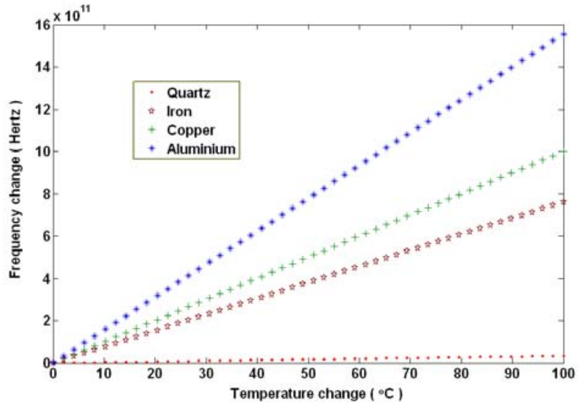

Fig. 3 (a) Frequency change of slave laser frequency with temperature change of slave laser cavity for different materials of the cavity

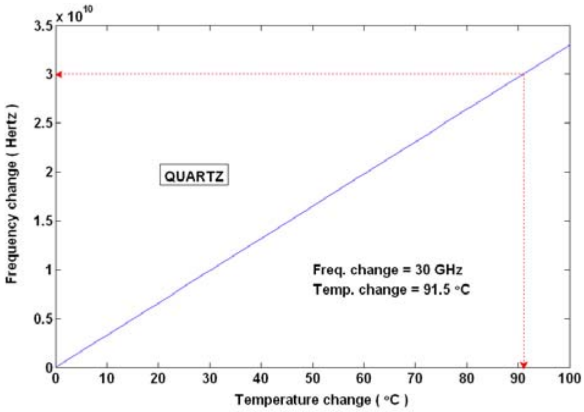

Fig. 3 (b) Frequency change of quartz type slave laser cavity with change of temperature

The two injection-locked signals from the two slave laser sources are fed to a fast-response photo detector (typically a HEMT device) as shown in Fig. 1, at the output of which the beat frequency signal is obtained. The HEMT device output current is given by:

$$I_s = \beta_0 V_c[1-(1+2V_g/V_c^{-1/2}].(nkT/q)$$
$$\ln[1+q\eta P_0\{1+m\cos(2\pi f_1 t)\}/I_{dark}.h\nu]$$
$$+b_1[V_{gb}+V_s.2.\cos(2\pi f_1 t+2\pi f_2 t+\varphi)$$
$$\cos(2\pi f_1 t-2\pi f_2 t-\varphi)/2] \quad (8)$$

where the symbols have their usual significance. The plot of output current from the HEMT i.e. the photo detector is shown in Fig. 4, whose envelope represents the desired 60 GHz millimeter-wave signal which can be filtered out with a suitable filter.

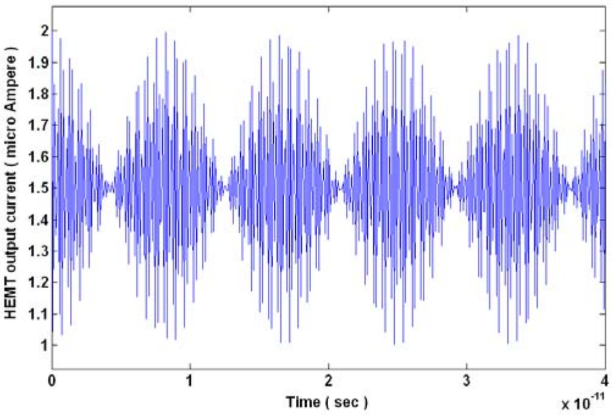

Fig. 4 HEMT output current whose envelope is the 60 GHz signal

To make the analysis general, we may introduce a phase-shift, φ in the optical signal from one of the slave lasers when the photodiode output current will be given by:

$$I_s \propto \hat{E}_1\hat{E}_2\cos[(\omega_2-\omega_1)t+\varphi] \quad (9)$$

This will help us to investigate the effect of phase difference, if any, between the optical signals from the two slave laser sources, when two separate slave lasers are used [6]. The optical phase shifter we are considering here is a dispersion type phase shifter [7] whose principle is shown in Fig. 5. It may now be observed from Fig. 6 that the HEMT output signal is severely affected if $\varphi \neq 0$ between the two signals from the slave lasers.

This plot has been generated for sub-millimeter wave signal as the output of the photo detector, because higher the frequency more severe is expected to be the effect of phase de-coherence. This result in Fig. 6 indicates that when two separate slave lasers are used, in addition to being injection locked, single mode fiber is to be used to feed the optical signals from the slave lasers to the photo detector. If this is not done then phase de-coherence, if any, introduced by the fiber will severely affect the millimeter-wave or sub-millimeter wave signal characteristics obtained at the output of the photo detector.

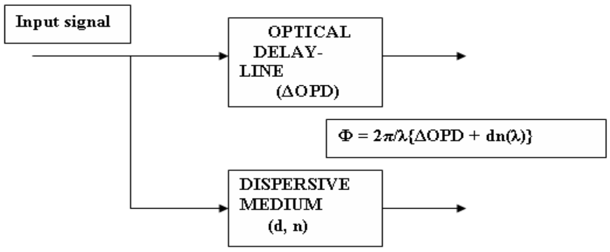

Fig. 5 Dispersion type phase-shifter

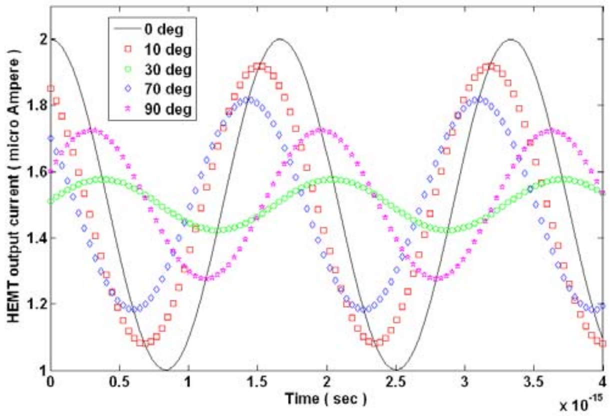

Fig. 6 Effect of phase de-coherence between the two slave laser sources

IV. Conclusion

A novel technique has been developed to generate ultra-stable millimeter-wave signal with optical heterodyning of injection-locked signals from two slave lasers whose frequency is locked to the desired FM sidebands of a master laser source. This technique may be useful for new and emerging applications of electronic communication systems demanding very low-phase noise millimeter-wave/sub millimeter-wave signal.

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References

[1] L.N. Langley, M.D. Elkin, C. Edge, M.J. Wale, U. Gliese, X. Huang, and A.J. Seeds, "Packaged semiconductor laser optical phase locked loop (OPLL) for photonic generation, processing, and transmission of microwave signals", IEEE Trans. Microwave Theory Tech., vol. 47, pp.1257-1264, July 1999.
[2] H. Olsen and G. Jacobson, "A theoretical and experimental analysis of modulated laser fields and power spectra", IEEE J, Quantum Electronics, vol. 18, pp. 2069-2080, 1982.
[3] A.B. Carlson: "Communication Systems", McGraw-Hill, New York.

[4] S. Kobayashi and T. Kimura, "Injection locking in AlGaAs semiconductor laser", IEEE J, Quantum Electronics, vol. 17, pp. 681-689, 1981.
[5] K. J. Kuhn: "Laser Engineering", Printice Hall, U.S.A.
[6] A. Seeds, "microwave applications for opto-electronics", Proc. ISSSE,92, pp. 171-181, Sept. 1 - 4, Paris, France
[7] A. L. Mierrment, "A chromatic phase shifter using adjustable dispersive elements", Proc. of SPIE, vol. 4, April 2000.

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