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NOISE REDUCTION IN THE MILLIMETER WAVE SIGNAL GENERATION USING AN OPTICALLY TRANSMITTED SUBHARMONIC REFERENCE

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Abstract

A novel approach for optical generation of millimeter waves is demonstrated in this paper. Only a subharmonic of the MMW signal is transmitted optically in this method. The MMW signal is generated by using the low-frequency subharmonic as a reference at the receiver side. The most important parameter of microwave link is the phase noise, hence the noise and signal power conditions were studied.

1. SYSTEM CONCEPT

Optical generation of millimeter waves is relevant for many practical applications, (mobil and indoor communications, intelligent vehicle routing, millimeter-wave picocells system, etc.) and there is an increasing demand for higher and higher carrier frequencies. However the, optical transmission of a millimeter wave (MMW) signal is a crucial problem. The well known methods (high speed external modulator is applied, two lightwaves are mixed, etc.) use MMW E/O converters at the transmitter part and MMW O/E converters at the reception part of the system. These components are rather complicated and expensive. Furthermore these system are sensitive for fiber dispersion. [1,2]

In our approach the optical parts of the system became less demanding due to the relatively low frequency of the optically transmitted subharmonic reference (less expensive and simpler optical transmitter and receiver are needed, the problem of the fiber dispersion is eliminated). The block diagram of the system is shown in **Fig. 1** concentrated on the carrier generation.

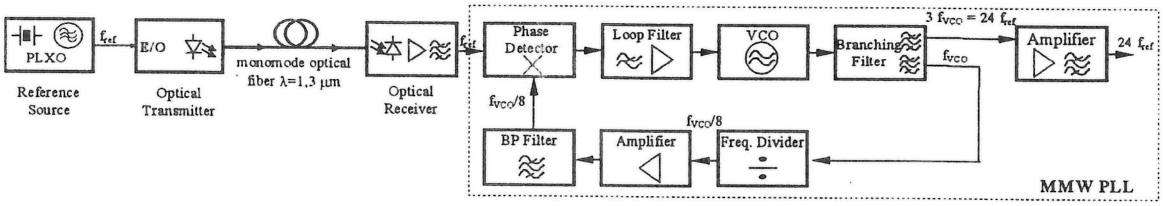

Fig. 1 Block diagram of the system

In the receiver the frequency of the fundamental signal of the harmonic Voltage Controlled Oscillator (VCO) ($n{\cdot}f_{ref}$, $n = 8$ in our case) is divided by a digital frequency divider. This signal is compared to the incoming optically transmitted subharmonic reference (f_{ref}) in the phase detector. The error signal is amplified, filtered and used to control the VCO frequency. One of the harmonic frequencies ($k{\cdot}f_{VCO}$, $k = 3$ in our case) is coupled out of the oscillator and utilized as a MMW carrier after proper amplification.

2. NOISE SOURCE OF SYSTEM

2.1. *Noise from directly modulated optical link*: A simple fiber optic link consists of a semiconductor laser diode, optical fiber, photodiode and electrical devices [3]. These components are the noise sources of the optical link. Because of independent noise sources, the electrical noise powers from optical link can be added:

$$N = N_P + N_L / L \qquad (1.)$$

where N_P and N_L are the noises of laser diode and photodiode respectively and L is the electrical loss of optical link.

a) The amplitude, power and frequency of the laser as an oscillator have some fluctuations. The semiconductor laser source is characterized by the relative intensity noise (RIN).

$$RIN(f) = \frac{\langle \Delta P^2(f) \rangle}{P_L^2} \qquad (2)$$

$\langle P^2(f) \rangle$: spectral density of the square of the laser optical power fluctuation
P_L : steady state optical power output from laser

The equivalent electrical noise power generated in the laser:

$$N_L(f) = RIN(f) \cdot P_L \cdot B \qquad (3)$$

where B is the bandwidth.

b) Several sources of optical loss along the link are indicated.

- L_{LF} : laser to fiber coupling loss (typical value: 3 dB)
- L_F : optical fiber loss (0.3 dB/km)
- L_C : connector and splice losses (0.1 – 0.4 dB)
- L_{FP} : fiber to photodiode coupling loss (<3 dB)

Hence the whole optical insertion loss of the link:

$$L_{opt} = P_L / P_P = L_{LF} + L_F + L_C + L_{FP} \qquad (4)$$

where P_P the optical power delivered to photodiode.

And the electrical insertion loss (L_{el}) which is proportional to the square of the optical loss .of the link:

$$L_{el} = \frac{P_{tr}}{P_{rec}} = \frac{I_{tr}^{\,2} \cdot R_L}{I_P^2 \cdot R_P} = \left(\frac{L_{opt}}{\eta_L \cdot \eta_P} \right)^2 \cdot \frac{R_L}{R_P} \qquad (5)$$

here P_{tr} and P_{rec} are the electrical power supplied to the laser diode and delivered by the photodiode, respectively. R_L is the laser diode incremental drive impedance about its point of bias, R_P is the photodiode load impedance, I_{tr} is the modulation current of the laser diode, I_P is the photo current of the photodetector and finally η_L and η_P are the responsibility of laser diode and photodiode, respectively.

c) Supposing a pin diode photo receiver the electrical noise power in the photodiode output comes from shot noise of average photocurrent (N_q), dark current (N_d), leakage current (N_l) and the Johnson noise of photodiode equivalent resistance (N_T). Although the main noise source are the thermal noise and the shot noise, which are due to the quantum statistic nature of photons and electrons. The noise sources are statistically independent, so they can be added and the resultant electrical noise power of photodetector (N_P) is:

$$N_P = N_q + N_d + N_l + N_T \cong N_q + N_T = 2 \cdot q \cdot I_{Ph} \cdot B \cdot R_P + k \cdot T \cdot B \qquad (6)$$

where q is the electron charges, k is the Boltzmann constant, T is the absolute temperature, B is the bandwidth and I_{ph} is the average photo current.

Examining the electrical signal power in the output of photodiode a sinusoidal modulating signal is assumed:

$$i_{rms} = \frac{1}{\sqrt{2}} \cdot I_P = \frac{1}{\sqrt{2}} \cdot \frac{q \cdot \eta_Q \cdot P_P}{h \cdot \nu} \qquad (7)$$

where h is the Plank constant and ν is the light frequency.

Hence the signal to noise ratio is:

$$\frac{S}{N} = \frac{(i_{rms})^2 \cdot R_P}{N_P + \frac{N_L}{L_{el}}} \tag{8}$$

Summarizing the noise performance and signal power of the direct modulated optical link, the block diagram and the computed results can be seen in **Fig. 2** and **Table 1**.

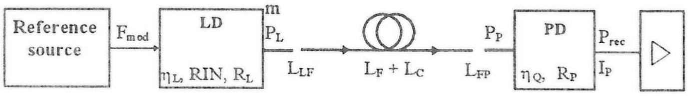

Fig. 2 Block diagram of direct modulated optical link

	Reference source	LD (DFB)	Optical fiber	PD (pin)
Transmission. of microwave signal	F_{mod}=1.055GHz	P_L = 1 mW η_L = 0.2 W/A λ = 1.3 μm	l = 20 km L_{opt} = 12 dB P_P = -12 dBm	η_P= 0.8 A/W I_d+I_s = 20 nA I_P = 120 μA i_{rms} = 17 μA **S = -42 dBm**
Noise	-120dBc/Hz @100kHz	RIN= -140 dBc/Hz m = 0.2	L = 24 dB	B = 0.5 MHz **N_P = -114 dBm N_L = -118 dBm** **N = -112 dBm**

Table 1. Computed values of signal and noise power

2.2. *Noise from reference oscillator and frequency multiplication in the MMW PLL:*

Frequency multiplication results in increased SSB phase noise at the higher output frequency.

$$a(f_m)_N = N^2\, a(f_m) \qquad a(f_m)_N[dBc/Hz] = a(f_m)[dBc/Hz] + 20\cdot\log N \tag{9}$$

where $a(f_m)$ is the SSB phase noise at fundamental frequency, $a(f_m)_N$ is the SSB phase noise at harmonic frequency and N is the multiplication factor [4]. In our case: $20\cdot\log 24 = 27.6\ dB$

As seen the reference oscillator is the most important device of the system from the noise performance point of view, because of the frequency multiplication. Thus a low phase noise reference oscillator is necessary, in our case this is a crystal oscillator with -120dBc/Hz phase noise at 100kHz.

3. OPTIMIZATION OF PPL

The millimeter wave signal generation multiplies the optically transmitted reference by a millimeter wave phase locked loop. This is a second order PLL with active filter so the closed-loop transfer function [5]:

$$H(S) = \frac{K_o \cdot K_d \cdot F(S)}{S + K_o \cdot K_d \cdot F(S)} = \frac{2\cdot\xi\cdot\omega_n\cdot S + \omega_n^2}{S^2 + 2\cdot\xi\cdot\omega_n\cdot S + \omega_n^2} \tag{10}$$

$$F(S) = -\frac{S\cdot\tau_2 + 1}{S\cdot\tau_1} = -\frac{S\cdot C\cdot R_2 + 1}{S\cdot C\cdot R_1} \tag{11}$$

Where ω_n is the natural frequency of the loop, ξ is the damping factor, $F(S)$ is the transfer function of loop filter, K_o is the VCO gain factor and K_d is the phase detector gain factor.

By the optimization of the loop filter parameters (bandwidth, damping-factor etc.) the VCO noise can be suppressed in the vicinity of the carrier and the noise properties of the system can be further improved. Almost always this optimum is only a compromise, because of two general reasons. The loop bandwidth should be as narrow as possible to minimize output jitter due to the reference noise, but the loop bandwidth should be as wide as possible to obtain good acquisition and tracking as well as to minimize the output jitter due to the internal oscillator (VCO) noise.

4. EXPERIMENTAL RESULTS

The measured results of the experimental system are presented in **Figs. 3a** and **3b**. The spectra of the reference signal, VCO free running signal, and locked PLL signal at 1.055GHz are shown in **Fig.3a**. The measured power spectrum at the third harmonic of VCO after amplification (25.32GHz) is plotted in **Fig.3b**.

The measured SSB phase noise at reference signal and harmonic signal are shown in **Fig. 4**. The phase noise increasing according to theory of noise increasing because of frequency multiplication. It can be seen the multiplied reference signal is dominant in the phase noise. So, if we want to reduce the phase noise of harmonic signal a lower phase noise crystal reference oscillator is necessary.

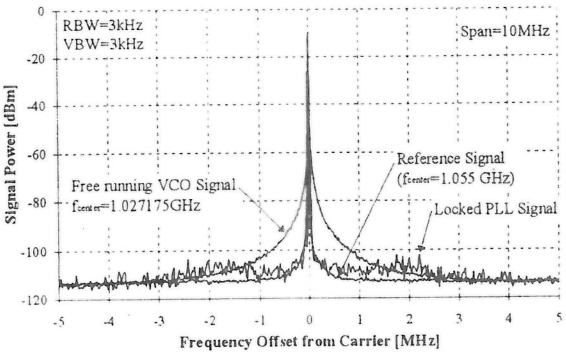

Fig. 3a Power spectra of the fundamental and reference frequencies

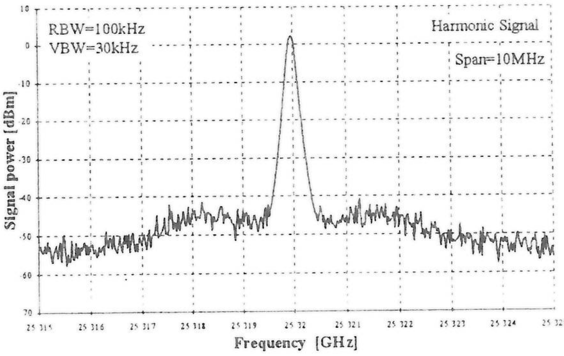

Fig. 3b Power spectrum of the harmonic frequency

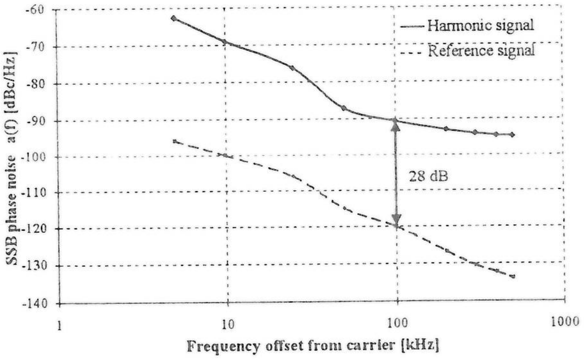

Fig. 4 SSB phase noise

CONCLUSION

An alternative method for optical generation of millimeter waves was examined in this paper considering the noise conditions. The main advantage of this method is that with the application of relative simple and inexpensive optical devices a low noise millimeter wave signal can be optically generated.

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