# Optical Wireless: Coherent Detection of Very Narrow Linewidth Millimeter-wave and Microwave Signals

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## Abstract

Optical wireless offers broadband telecommunication services within buildings and avoids utilizing the already-congested radio spectrum. Because of safety reasons, optical transmission power in optical wireless local-area networks (LAN's) is restricted to a level that may severely degrade the system performance. A coherent-detection technique for very narrow linewidth millimeter-wave and microwave "subcarrier" signals is demonstrated to improve receiver sensitivity, without using expensive optical amplifiers.

## 1. Introduction

Wireless local-area networks (LAN's) have been proposed to provide telecommunication services, such as mobile phones, electronic mails, data transfer, and multi-media, within confined environments (e.g., offices) because they allow easy hardware reconfiguration, portability, and reduction of cables [1]. Traditionally, wireless communication uses radio and/or microwave (i.e., subcarrier) techniques. However, the radio spectrum (of about 20-30 MHz) is a very limited resource and will get congested easily as the traffic demand rises; thus limiting the broadband capability of wireless transmission for densely populated environments. Therefore, optical wireless, offering much wider bandwidth, is an alternative. In addition, optical radiation is highly containable and does not interfere with other electronic systems in the service area.

As a result, the issues facing the development of optical wireless systems, such as optical safety and involved technology, have been studied [1]. To ensure that the optical radiation posses no harm to human (i.e., eyes and skin), various national and international standards on laser safety, such as IEC825, has been published to specify the safe optical emission levels from lasers [2]. In addition, to reduce particularly the danger of eye damage, diffusely scattering transmission is proposed, where optical signals, usually in the form of millimeter-wave or microwave "subcarriers", generated from various locations in an office are directed to and distributed uniformly on a hologram at the ceiling, and then downward-broadcasted to the whole area. As mentioned in [1], for a typical office with a floor area of 10 m by 10 m, the transmitter power required (assuming a receiver collection area of 1 $\mathrm{cm}^2$) is 100 mW, which is well beyond the acceptable safety limits, for 0.1 $\mu$W receiver sensitivity.

As in the technological aspect, a simple and potentially low-cost method for optical generation of very narrow linewidth millimeter-wave and microwave subcarrier signals for optical wireless LAN's and mobile/personal communications has been demonstrated [3]. This technique uses a properly biased Mach-Zehnder waveguide modulator to introduce a millimeter-wave or microwave subcarrier onto the intensity of a wide-linewidth continuous-wave (CW) semiconductor laser. A frequency-modulated optical signal with two strong components separated by twice the subcarrier frequency are generated. Coherently mixing of these two components at a photodiode results in an electrical signal with linewidth depending only on the electrical source that drives the modulator.

However, the conversion efficiency from the electrical to the optical domain at the modulator is relatively low. Together with the restriction on the maximum permissible laser exposure, the transmitted power of the optical subcarriers is very limited and the system performance may be severely degraded. Although the degradation can be overcome by deploying high-gain optical amplifiers at the front-end of receivers, it may not be justified in some situations because of the cost or some pre-existing physical constraints. In addition, channel tunability may also be an important factor to consider.

Therefore, a "coherent-detection" technique may serve as a very good alternative in such systems, since it provides improved sensitivity (i.e., theoretically, by at least 10 dB) and also supports a wide channel-tuning range [4]. In the proposed technique, photodiodes are used solely for converting the frequency-modulated optical signals into intermediate-frequency (IF) electrical signals. Coherent-mixing of the strong IF components through a nonlinear (e.g., square-law) operation results in a phase-noise-canceled signal at the receiver. Therefore, cheap, wide-linewidth semiconductor lasers can still be used to keep the cost down.

## 2. Operation Principle

Shown in Fig. 1, the set-up of the transmitter is basically the same as the one described in [3]. Since the operation of the Mach-Zehnder modulator, which introduces a subcarrier onto the intensity of a CW laser source, has been described, the frequency-modulated optical signal $E(t)$ with proper DC bias (i.e., $V_\pi$) at the modulator and a subcarrier $\frac{1}{2}f_s$, without going through the derivation in detail, is given by

$$E(t) \propto \sum_{\substack{n=-\infty \\ n=\text{odd}}}^{\infty} 2J_n(\Phi)e^{j(2\pi f_c t + \theta_c(t) + 2\pi n(\frac{1}{2}f_s)t + \frac{1}{2}\pi)}, \tag{1}$$

where $f_c$ is the laser carrier frequency, $\theta_c(t)$ is the laser phase noise, and $\Phi$ is the phase modulation depth, controlled by the subcarrier amplitude. $J_n(\Phi)$ is the Bessel function of the first kind with integer order $n$. For $\Phi$ within the range of interest (i.e., $\Phi = [1.0, 1.5]$ rad), only those terms with $J_{\pm1}(\Phi)$ and $J_{\pm3}(\Phi)$ contribute appreciably.

Also shown in Fig. 1, the receiver consists of a local oscillator (LO) laser, a photodiode, and a square-law device. Here, polarization fluctuations and intensity noise of the optical signal and LO laser signal are ignored for simplicity, otherwise the standard polarization-diversity and dual-balanced detector configurations are added to the receiver with some minor modifications [5], [6]. The desired IF signal (i.e., channel tuning) is selected by tuning the center frequency of the LO laser. Also, a bandpass filter can be added here to reduce unwanted noise and interference. The resulting photocurrent can be approximated as

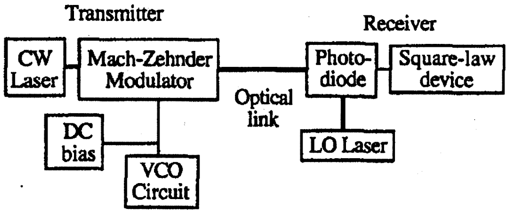

Figure 1: Block diagram of the transmitter and receiver

$$i(t) \approx i \sum_{\substack{n=-3 \\ n=\text{odd}}}^{3} 2J_n(\Phi)\cos(2\pi f_{IF}t + \theta_{IF}(t) + 2\pi n(\frac{1}{2}f_s)t + \frac{1}{2}n\pi), \tag{2}$$

where $i$ is the photocurrent converted from the received optical signal and LO power, $f_{IF}$ is the IF carrier frequency, and $\theta_{IF}(t)$ is the total IF phase noise (i.e., including the LO laser phase noise). The square-law device allows the strong components of the IF signal being coherently mixed together and results in a photocurrent

$$\begin{aligned} i(t) \approx\ & DC \text{ terms} + 2f_{IF} \text{ terms} + 2i^2[(J_1^2(\Phi) - 2J_1(\Phi)J_3(\Phi))\cos(2\pi \cdot f_s t) \\ & -2J_1(\Phi)J_3(\Phi)\cos(2\pi \cdot 2f_s t) + J_3^2(\Phi)\cos(2\pi \cdot 3f_s t)]. \end{aligned} \tag{3}$$

The third (i.e., $f_s$) term represents the desired phase-noise-canceled signal, while other undesired terms can be filtered out by a narrowband bandpass filter.

## 3. Experiment

In the experiment, the coherent-detection technique is demonstrated at $f_s$ = 600 MHz (i.e., the subcarrier frequency) with $f_{IF}$ = 200 MHz laser IF linewidth. Although a higher subcarrier frequency, such as 36 GHz demonstrated in [3], can be used, 600 MHz is chosen with an eye toward demonstrating the phase-noise-canceling capability of this technique. A microwave subcarrier of 300 MHz is first generated by a voltage-controlled oscillator (VCO) circuit. The subcarrier amplitude is adjusted to give a phase modulation depth of approximately 1.36 rad to optimize the signal-to-noise ratio (SNR) at the receiver output. In addition, a DC bias voltage of about 4 V is applied to the modulator. Two single-mode DFB lasers, each with center wavelength in the vicinity of 1.321 $\mu$m and linewidth of about

100 MHz, are used as the source and LO lasers, which also have CW power of about 0.7 mW and 1.0 mW, respectively. In the actual measurement, the IF is tunned to 10.76 GHz and a laser IF linewidth of 200 MHz is measured by a microwave spectrum analyzer.

Shown in Fig. 2 is the IF spectrum of the detected signal with the proper DC bias, where the two strong (i.e., first-harmonic) components are shown with 600 MHz separation. Note that the high spectral level between the two peaks is caused solely by the wide phase-noise sidebands. Other harmonic components are, however, too weak and can not be seen in the figure. The spectrum after the square-law device (i.e., a microwave coaxial detector) is shown in Fig. 3. The desired signal, whose linewidth is now limited by the bandwidth resolution of the spectrum analyzer, is found at 600 MHz. The weak harmonic signal at 1.2 GHz is found about 20 dB below the peak power of the desired signal, which agrees with the theoretical calculation [4].

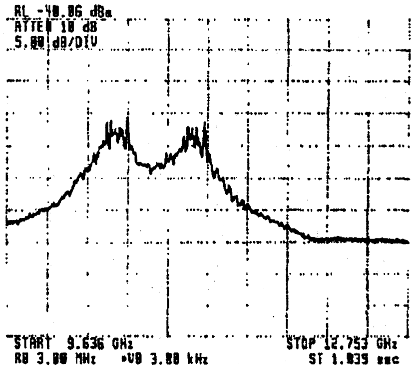

Figure 2: IF spectrum of optical signal with proper DC bias

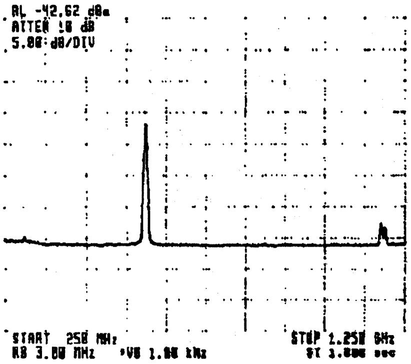

Figure 3: Spectrum of the phase-noise-canceled signal after the square-law device

## 4. Summary

A coherent-detection technique for very narrow linewidth subcarrier signals is demonstrated. Wide channel-tunability and improved receiver sensitivity (i.e., theoretically, at least 10 dB better than that of direct detection) are provided with cheap, wide-linewidth semiconductor lasers, without using expensive optical amplifiers. Therefore, this technique is particularly suitable for low-cost, power-limited optical wireless LAN's using subcarrier technique.

## 5. Acknowledgements

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