Coherent demodulation of microwave signals by using optical heterodyne technique with applications to point to point indoor wireless communications systems.

A García-Juárez¹, I E Zaldívar-Huerta², G Aguayo-Rodríguez², J Rodríguez-Asomoza¹, M R Gómez-Colín¹, A G Rojas-Hernández¹

¹Universidad de Sonora (México).
²Instituto Nacional de Astrofísica, Óptica y Electrónica (México).
³Universidad de las Américas-Puebla (México).

E mail: agarcia@cifus.uson.mx

Abstract. An optical communications system using a couple microstrip antennas for distributing point to point analog TV with coherent demodulation based on optical heterodyne in close vicinity is reported in this paper. In the proposed experimental setup, two optical waves at different wavelengths are mixed and applied to a photodetector. Then a beat signal with a frequency equivalent to the spacing of the two wavelengths is obtained at the output of the photodetector. This signal corresponds to a microwave signal located at 1.25 GHz, which it is used as a microwave carrier in the transmitter and as a local oscillator in the receiver of our optical communication system. The feasibility of this technique is demonstrated transmitting a TV signal of 66-72MHz.

Keywords: Microwave photonics, optical heterodyne, microwave generation, microwave carriers, wireless communications, processing of microwave signals, coherent demodulation.

1.-Introduction
Over the past few years, there has been an increasing effort in researching new design of indoor wireless communications systems, due to connectivity that they show in a room or in a building. Currently, several companies of telecommunications use purely omnidirectional antennas in their wireless routers to transmit data to laptops in close vicinity [1]. The properties of microstrip patch antennas and arrays with their planar configuration exhibit an attractive option for indoor communications where the gain is considerably enhanced. On the other hand, the generation of microwave and millimetre-wave (mm-wave) signals by using photonic technique are being used in radio-over-fibre (RoF) systems, distribution antenna systems, broadband wireless access networks, and radar systems etc. In all these applications the microwave signals are generated at a remote central station and distributed transparently to several simplified antenna stations via optical fiber [2].

³Further author information: (corresponding author Alejandro García Juárez)
E-Mail: agarcia@cifus.uson.mx
The main goal of these systems is to reduce infrastructure cost and to overcome the capacity bottleneck in wireless access networks, allowing, at the same time, flexible merging with conventional optical access networks. Thus, in order to design a reliable RoF-based access network infrastructure, RoF techniques must be capable of generating the microwave signals and allow a reliable microwave signals transmission over the optical link. For this purpose, several RoF techniques have been proposed in the past few years. For broadband wireless systems and distribution antenna systems operating at microwave and millimeter-wave carriers, several photonic techniques for generating microwave signals have been proposed. Among the most common used techniques are: optical heterodyning [3], optical injection locking [4], optical frequency/phase locked loops (OFLL/OPLL) [5], microwave generation using external modulation [6]. Optical injection locking [7] and optical phase-locked loops (OPLL) [8] are expensive in practice. The use of external intensity modulation generates frequency doubling or quadrupling of the driven RF sinusoid signal [9]. This method requires an external modulator which increases both loss and cost, and is more susceptible to bias drifting of the modulators, which can affect the output spectrum. The key advantage for generating microwave or millimeter-wave signals by optical means is that very high-frequency signals with very low phase noise and high purity can be generated. By using optical heterodyne technique it is very easy to tune frequencies with a spectral linewidth of a few ten MHz and over a wide range by simply tuning the wavelength of the two optical input signals; the obtained frequencies are limited only by the photodetector bandwidth [10]. Besides, the generated signals by using this technique can be generally used as both information carriers, and as a local oscillator for transmitting and receiving both analog and digital information signals by using not only RF schemes but also through an optical fiber. In this sense, an optical communications system using a couple microstrip antennas for transmitting and receiving information with coherent demodulation based on optical heterodyne scheme is proposed in this paper, where our main goal is to show potential applications of the photonic generation of microwave signals for distributing point to point analog TV signals by using microstrip antennas. The remainder of this paper is structured as follows. A brief theoretical description of the optical heterodyne technique and the experimental scheme for generating microwave signals is presented in section 2. A theoretical description of the modulation and demodulation will be presented in section 3. The proposed transmission system is described in section 4. Finally, we show our conclusion to this work in section 5.

2.- Optical heterodyne technique

The basic principle for generating microwave carriers is based on optical heterodyne technique, it represents a physical process called optical beating or frequency beating, where two phase-locked optical sources with angular frequencies $\omega_1$ and $\omega_2$ are superimposed and injected into a high frequency photodetector that permits to obtain a photocurrent at a frequency $\omega_2 - \omega_1$. To explain this in more detail, let us consider the relation between the generated electrical output signal and the two superimposed optical input waves from a more physical point of view. For simplicity, we assume that the two optical input waves are linearly polarized monochromatic plane waves in the infrared which propagate in the +z direction. Let

$$E_1 = \hat{E}_1 \exp\left[i(\omega_1 t - k_1 z + \varphi_1)\right] e_1,$$  \hspace{1cm} (1)

and

$$E_2 = \hat{E}_2 \exp\left[i(\omega_2 t - k_2 z + \varphi_2)\right] e_2,$$  \hspace{1cm} (2)

be the complex electrical field vectors of the two optical waves, with field amplitudes $\hat{E}_1$ and $\hat{E}_2$, angular frequencies $\omega_1$ and $\omega_2$ and wave numbers $k_1$ and $k_1$. The phase of each optical input wave is considered by $\varphi_1$ and $\varphi_2$ and $e_1$ and $e_2$ are the unit vectors determining the orientation of the
electrical field vector of the linearly polarized optical input waves. The intensities of the constituent waves are given by the magnitude of their Poynting vectors and are therefore given by [11]

\[ I_1 = \frac{1}{2} \left( \frac{\varepsilon}{\mu} \right)^{\frac{1}{2}} |E_1|^2. \]  

(3)

\[ I_2 = \frac{1}{2} \left( \frac{\varepsilon}{\mu} \right)^{\frac{1}{2}} |E_2|^2. \]  

(4)

If the two incident optical waves are perfect plane waves and have precisely the same polarization \((e_1 = e_2)\), the resulting electrical field \(E_o\) of the optical interference signal is the sum of the two constituent input fields and hence we can write \(E_o = E_1 + E_2\). Taking the squared absolute value of the optical interference signal we obtain

\[ |E_o|^2 = |E_1 + E_2|^2 = |E_1|^2 + |E_2|^2 + E_1^* E_2 + E_1 E_2^* \]

\[ = |E_1|^2 + |E_2|^2 + 2|E_1||E_2|\cos((\omega_2 - \omega_1)t - (\phi_2 - \phi_1)). \]  

(5)

From equation (5) and by using equations (3) and (4), it follows that the intensity of the interference signal \(I_o\) is given by [11]

\[ I_o = I_1 + I_2 + 2(I_1 I_2)^{\frac{1}{2}} \cos((\omega_2 - \omega_1)t - (\phi_2 - \phi_1)). \]  

(6)

By launching this optical interference signal into a photodetector, a photocurrent \(i\) is generated which can be expressed as [11]

\[ i = \frac{\eta_o q}{h f_1} P_1 + \frac{\eta_o q}{h f_2} P_2 + 2 \frac{\eta f q}{h} \left( \frac{P_1 P_2}{f_1 f_2} \right)^{\frac{1}{2}} \cos((\omega_2 - \omega_1)t - (\phi_2 - \phi_1)), \]  

(7)

where \(q\) is the electron charge and \(P_1\) and \(P_2\) denote the optical power levels of the two constituent optical input waves. The photodetector’s DC and high-frequency quantum efficiencies are represented by \(\eta_o\) and \(\eta_f\). It is of course important to consider that the detector’s quantum efficiency is not independent of the frequency. Several intrinsic and extrinsic effects such as transit time limitations or microwave losses will eventually limit the high-frequency performance of the detector and thus the detector’s DC responsivity \(\eta_o\) is typically much larger than its high-frequency responsivity \(\eta_f\). In our case, we can further simplify the photocurrent equation (equation (7)) by considering the fact that the two optical input waves are close in frequency \((f_1 \approx f_2)\) whereas the difference frequency \(f_c\) is by far smaller \((f_c = \left| f_2 - f_1 \right| \ll f_1, f_2)\). If we further assume for simplicity that the power levels of the two optical input waves are equal \((P_{opt} = P_1 = P_2)\), equation (7) becomes [11]

\[ i = 2 s_o P_{opt} + 2 s_f P_{opt} \cos(2\pi f t + \Delta \phi). \]  

(8)

Where \(\Delta \phi = \phi_2 - \phi_1\). Here \(s_o = \frac{\eta_o q}{h f}\) and \(s_f = \frac{\eta_f q}{h f}\) are the photodetector’s DC and high frequency responsivities given in A/W. Equation (8) is the fundamental equation describing optical heterodyning in a photodetector. The first term is the DC photocurrent generated by the constituent
optical input waves and the second term is the desired high-frequency signal oscillating at the
difference frequency \( f_c \) (down-converter) or intermediate frequency (IF) [12]. In our case it
represents the microwave signal that we will use as both information carriers, and as a local oscillator
for transmitting and receiving TV signals in a wireless communication system.

2.1 Experimental scheme for generating microwave signals
The heterodyne technique for generating microwave signals has been done using the experimental
setup shown in figure 1. In this experiment we have used two laser diodes emitting at different
wavelengths, one of them was a tunable laser (New Focus, model TLB-3902) which can be tuned over
the C band with a channel spacing of 25 GHz, and the other one is a fiber coupled DFB laser source
(Thorlabs, model S3FC1550) with a central wavelength at 1550 nm. For the generation of the
microwave signals, the outputs of both lasers are coupled to optical isolators to avoid a feedback into
the lasers and consequently instabilities to the system. A pair of polarization controllers was used to
minimize the angle between the polarization directions of both optical sources. Thus, the polarization
of the light issued from each optical source is matched and therefore, there was no degradation of the
power levels in the microwave signals generated from the photodetector. The output of each controller
is launched to a 3dB coupler to combine both optical spectrums. After that, an optical output signal is
received by a fast photodetector (MITEQ model SCMR-50K6G-10-20-10) with a typical gain of 25
dB, and –3 dB bandwidth of 6 GHz. The resulting photocurrent from the photodetector corresponds to
the microwave beat signal which is analyzed with an Electrical Spectrum Analyzer (ESA), (Agilent
model E4407B). The other optical output resulting from optical coupler was applied to an Optical
Spectrum Analyzer (OSA) (Anritsu model MS9710C), for monitoring the wavelength of the two
beams.

\[
\Delta f = \frac{c}{\lambda_1} - \frac{c}{\lambda_2} = \frac{c}{\lambda_1 \lambda_2} \left( \frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2} \right) \approx \frac{c}{\lambda^2} |\Delta \lambda|, \quad (9)
\]

DFB laser can be used to control not only the output power of the fiber coupled laser diode, but also
the precise control of the temperature at which the laser is operating. Both controls can be used to tune
the fiber coupled laser diode to an optimum operating point, providing a stable output. In this way, we
observed that the wavelength of the DFB laser was shifting, by varying its temperature with a scale of
1ºC. Consequently, the beat signal frequency was continuously tuned from 0 to 10 GHz.

Figure 2(a) illustrates the spectrums of three microwave signals generated with optical heterodyne technique.
The generated signals are located at 1.4, 4.9 and 9 GHz when the temperature of the DFB
laser, with an optical fixed power of 2.4 mW, was tuned at 22.8ºC, 23.2ºC and 23.7ºC respectively.
Figure 2(b) shows the optical spectrums of the optical signal from both lasers. From this figure, we
can see that the wavelength difference between both lasers is 0.072nm and it corresponds to the beat
signal frequency of 9 GHz as shown in figure 2(a). The frequency difference from both lasers can be
expressed by [13]

\[
\Delta f = \frac{c}{\lambda_1} - \frac{c}{\lambda_2} = \frac{c}{\lambda_1 \lambda_2} \left( \frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2} \right) \approx \frac{c}{\lambda^2} |\Delta \lambda|, \quad (9)
\]
where $\lambda_1$ and $\lambda_2$ are the wavelengths of the two beams, respectively, and $\Delta \lambda$ is the difference between the two wavelengths. From the result shown in figure 2(b), we can observe that the generated microwave signal is in good agreement with theoretical expression of equation (9). Therefore, when one laser source is operating at a fixed wavelength and the other is being continuously tuned, the beat frequency will shift correspondingly.

![Figure 2. Microwave signals and optical mixing. (a) Microwave spectrums continuously tuned from 0 to 10 GHz, (b) optical spectrum corresponding to the two combined optical beams with spectral separation of 9GHz.](image)

3.-Modulation and demodulation

Some form of modulation is always needed in an RF system to translate a baseband signal (e.g., audio, video, data) from its original frequency bandwidth to a specified RF frequency spectrum. There are many modulation techniques, for example, AM, FM, amplitude shift keying (ASK), frequency shift keying (FSK), phase shift keying (PSK), biphase shift keying (BPSK), quadruphase shift keying (QPSK), 8-phase shift keying (8-PSK), 16-phase shift keying (16-PSK), minimum shift keying (MSK), and quadrature amplitude modulation (QAM). AM and FM are classified as analog modulation techniques, and the others are digital modulation techniques [14]. In this section we describe the AM modulation and demodulation due to it was used in our proposed wireless communication system.

3.1 Amplitude modulation

Analog modulation uses the baseband signal (modulating signal) to vary one of three variables: amplitude $A_c$, electrical frequency $(\omega_1 - \omega_2) = \omega_c = 2\pi f_c$; or phase $(\phi_1 - \phi_2) = \Delta \phi$. According to equation (8), the obtained carrier signal by using optical heterodyne technique can be written by

$$p(t) = A_c \cos((\omega_1 - \omega_2)t + \phi_1 - \phi_2) = A_c \cos(2\pi f_c t + \Delta \phi).$$

(10)

Where $A_c = 2s_j P_{opt}$. In amplitude modulation, if we assume that $s(t)$ is the information signal, and considering $A_c = 1$, $\Delta \phi = 0$, then a modulated signal can be written by

$$g(t) = s(t) \cos 2\pi f_c t .$$

(11)

Applying the modulation property of the Fourier transform to equation (11), we can find the density spectral of $g(t)$ is
Amplitude modulation therefore translates the frequency spectrum of a signal by ±f_c hertz, but leaves the spectral shape unaltered. This type of amplitude modulation is called suppressed-carrier because the spectral density of g(t) has no identifiable carrier in it, although the spectrum is centered at the frequency f_c.

3.2 Amplitude demodulation
Recovery the signal information s(t) from the signal p(t) requires another translation in frequency to shift the spectrum to its original position. This process is called demodulation or detection. Because the modulation property of the Fourier transform proved useful in translating spectra for modulation, we try it again for demodulation. Assuming that \( g(t) = s(t)\cos(2\pi f_c t) \) is the transmitted signal, we have

\[
g(t)\cos(2\pi f_c t) = s(t)\cos^2(2\pi f_c t) = \frac{1}{2} s(t) + \frac{1}{2}\cos(4\pi f_c t).
\]

(13)

Taking the Fourier transform of both sides of equation (13) and using the modulation property, we get

\[
\mathcal{F}\left[ g(t)\cos(2\pi f_c t) \right] = \frac{1}{2} S(f) + \frac{1}{4} S(f + 2f_c) + \frac{1}{4} S(f - 2f_c).
\]

(14)

The mathematical process described in this section can be obtained by convolving the spectrum of the received signal g(t) with that of \( \cos(2\pi f_c t) \) (i.e., with impulses at ±f_c). A low-pass filter is required to separate out the double frequency terms from the original spectral components. Obviously we need a filter with a cut frequency \( f_{cut} > 2f_m \) for proper signal recovery. In this case \( f_m \) represents the information frequency.

3.3 Effects in frequency and phase variations
When the local oscillator at the receiver, has a small frequency error \( \Delta f \) and a phase error \( \Delta \theta \), then this signal can be written as

\[
p_L(t) = \cos\left[ 2\pi(f_c + \Delta f)t + \Delta \theta \right].
\]

(15)

Assuming again that \( g(t) = s(t)\cos(2\pi f_c t) \) is the transmitted signal; then we have that at the receiver, the recovered signal can be written by

\[
g(t)\cos\left[ 2\pi(f_c + \Delta f)t + \Delta \theta \right] = s(t)\cos(2\pi f_c t)\cos\left[ 2\pi(f_c + \Delta f)t + \Delta \theta \right]
\]

\[
= s(t)\left( \frac{\cos(2\pi \Delta ft + \Delta \theta)}{2} + \frac{\cos(2\pi(2f_c + \Delta f)t + \Delta \theta)}{2} \right).
\]

(16)

The second term on the right hand side of equation (16) is centered at ±2f_c + \Delta f and can be filtered out by using a low pass filter. The output of this filter \( s_f(t) \) will then be given by the remaining term in equation (16).
\[ s_F(t) = \frac{1}{2} \left[ s(t) \left( \cos 2\pi(\Delta f) t \cos(\Delta \theta) - \sin 2\pi(\Delta f) t \sin(\Delta \theta) \right) \right]. \] (17)

As can be seen from equation (17), the output signal is not \( \frac{s(t)}{2} \), unless both \( \Delta f \) and \( \Delta \theta \) are zero. The effects of both frequency errors and random phase errors render this demodulation of the signal unsatisfactory. It is necessary, therefore, to have synchronization in both frequency and phase between the transmitter and the receiver when amplitude modulation is used. The synchronization of the carrier signals presents no major problem when the transmitter and the receiver are in close proximity. Recovering the original signal \( s(t) \) from the modulated signal \( g(t) \) using a synchronized oscillator is called coherent demodulation. In our case we take advantage of proposed optical heterodyne technique permits to obtain microwave carrier and local oscillator simultaneously in the transmitter and receiver respectively.

4. Transmission of TV signals by using heterodyne technique

In order to show a potential application of optical heterodyne technique in the field of the wireless communications, we have proposed a coherent system that although is not a truly wireless communication system, since an optical fiber is required to deliver both microwave carrier and local oscillator for transmitting and receiving information of TV signals by using a couple of microstrip antennas, we have used it as an approximation to point to point indoor wireless communications systems as shown in figure 3. From the photodetector 1 in the transmitter, a microwave signal located at 1.25GHz was obtained and mixed with an analog TV signal located at 62.25MHz. Then the resulting signal was amplified before being applied to a microstrip yagi antenna. After that, the obtained modulated signal was transmitted through a point to point wireless link by using a microstrip yagi antenna. Finally in the receiver, another microstrip yagi antenna received the transmitted information, which it was processed using optical heterodyne technique again to recover in this case the TV signal (66-72MHz). From the photodetector 2 in the receiver, a local oscillator that is synchronized, in frequency as well as in phase with that obtained from the photodetector 1, was mixed with the received signal. Then the resulting signal was filtered and the power spectral density obtained was displayed in an electrical spectrum analyzer, where it is analyzed to measure the power level of recovered information.

![Diagram of optical heterodyne technique](image)

**Figure 3.** Optical point to point wireless link for transmitting and receiving TV signals
Figure 4, clearly shows the spectrums of an analog TV channel around 1.25 GHz. We can observe in figure 4(a) that the power level transmitted was approximately of -36 dBm, while the frequency spectrum of the received signal as shown in figure 4(b) was attenuated 12 dB. However analog TV channel transmitted was satisfactorily recovered at the receiver.

Figure 4. Spectrums of TV signal around 1.25GHz. (a) transmitted, (b) received.

Figure 5(a) shows the frequency spectrum of an analog NTSC TV signal around 67.25MHz before being applied to frequency mixer, while the spectrum in figure 5(b) shows the analog TV channel 4 at the output of the receiver. In order to measure the quality of the received signal, is necessary to quantify the parameters of signal-to-noise ratio (SNR), differential gain and differential phase. Nevertheless it is not the aim of this paper. Here only we demonstrate that microwave signals generated by optical heterodyne can be used as carrier information in a wireless communication system and we have used a TV signal of test to verify it.

Figure 5. Spectrums of TV signal around 67.25MHz. (a) Transmitted, (b) received.

5.- Conclusion
Wireless communication systems require compact sources for the generation of mm-wave signals, that must have high spectral purity (linewidth < 100 kHz, phase noise < 100 dBc @100 kHz offset), tuneability, low power consumption and low cost, and although optical heterodyne of two DFB lasers has phase noise of ~75 dBc/Hz even at an offset frequency of 100 MHz and it does not very compact, we have demonstrated in this work that by using optical heterodyne technique, a TV signal was
transmitted and received satisfactory as a result of our proposed communication system generates a microwave carrier and a local oscillator simultaneously ensuring synchronization in frequency as well as in phase between microwave carrier and a local oscillator and avoiding in this case the use of an analog phase locked loop in the receiver to recover the TV information. The authors consider that the proposed scheme in this paper is not a truly wireless communication system, since an optical fiber is required to deliver the local oscillator in the receiver, however in order to obtain a wireless communication systems by using optical heterodyne technique, it is necessary to have collimated beams from optical fiber to photodetectors. On the other hand, due to the fact that the distribution of TV over microwave signals in the electrical domain presents loss associated with electrical distribution lines, the authors consider that the optical fiber is an ideal solution to fulfill this task because of its extremely broad bandwidth and low loss. In that case the distribution of TV over microwave can be directly by using optical fiber. The results obtained in this work ensure that as an interesting alternative, several modulation schemes can be used for transmitting not only analog information but also digital information. Besides as optical heterodyne technique described here can generate microwaves continually tuned, we can use this feature to transmit several TV signals using frequency division multiplexing schemes FDM and wavelength division multiplexing WDM techniques, not only point to point but also with bidirectional schemes by using simultaneous wired and wireless systems.

Acknowledgment

This work was supported by CONACyT (grant No 102046).

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