Intensity position modulation for free-space laser communication system

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\textbf{ABSTRACT}

In this research a novel modulation technique for free-space laser communication system called \textit{Intensity Position Modulation} (IPM) is carried out. According to $TEM_{00}$ mode of a laser beam and by linear fitting on the Gaussian function as an approximation, the variation of linear part on the reverse biased $pn$ photodiode produced alternating currents which contain the information. Here, no characteristic property of the beam as intensity or frequency is changed and only the beam position moves laterally. We demonstrated that in this method no bandwidth is required, so it is possible to reduce the background radiation noise by narrowband filtering of the carrier. The fidelity of the analog voice communication system which is made upon the IPM is satisfactory and we are able to transmit the audio signals up to 1Km.

\textbf{Keywords:} Modulation, Laser communication, $TEM_{00}$ mode, Gaussian profile, Analog communication, Linear approximation, Opto-mechanical modulator

\section{1. INTRODUCTION}

Free Space Laser Communication (FSLC) was one of the first applications proposed for laser technology in the early ‘60s. It is rapidly evolving area in communication that shows some advantages versus the electrical as security, no requirement for license, small antenna size, and low power consumption. Free-space laser communication offers a viable feature for intersatellite links and other applications where high performance links are a necessity.\textsuperscript{1,2}

Different modulation formats as Amplitude Modulation (AM), Frequency Modulation (FM), Phase Modulation (PM), are used in both analog and digital systems. In all of them a characteristic property of the beam like frequency, amplitude, or intensity changes proportional to the input signals. The required bandwidth depends on the type of the modulation and information signal. In this way, various modulators are developed and the rate of modulation has been restricted by modulator operation and detector response. The above cited properties of the laser beam are altered either by an external modulator or by a modulator internal to the laser cavity.\textsuperscript{3,4}

This paper describes an analog opto-mechanical modulation for FSLC system that has many differences from the others. In this procedure, during the modulation the basic properties of beam remain constant and only its position is changed due to the input information. We will see that the modulated carrier contains no frequency content or in the other words no bandwidth is required for a proper communication. As the first experiment, the present technique is used for audio signals of 50 Hz-4 KHz Speech, and with respect to the information demodulated in the receiver, operates in good manner with low distortion.
2. LINEAR APPROXIMATION ON THE GAUSSIAN FUNCTION

Principle of the method is based on the linearity of intensity distribution at \( TEM_{00} \) mode in one-half of the beam width. For this reason \( TEM_{00} \) mode has lesser expansion and more symmetry versus the higher order modes. According to the Gaussian distribution function for lowest order transverse mode we can write:

\[
I(x, y, z) = I_0 \frac{w_0^2}{w^2(z)} \exp\left(-2\left(\frac{x^2 + y^2}{w^2}\right)\right),
\]

(1)

where \( w \) is the spot size and \( I_0 \) will be the maximum intensity in the beam center.

Regarding to Eq. (1), we assumed a linear fitting on the area between the spot size and a point near the beam center, as is shown in Fig. 1. The linear fitted section will be the region from location \( C \) up to \( D \) and the amount of linearity is dependent upon the nearness of these locations. Point \( A \) can be found arbitrarily, and point \( B \) corresponds to the spot size. Beam divergence changes the slope of the linear part, so a well collimated beam is necessary to retain the spot size variation approximately at a desired value for the appropriate operation of the system.

3. MODULATION

For modulating process of a typical laser (e.g. Helium-Neon, or Diode), we used a thin coated mirror which is attached to the spider of a woofer loudspeaker. Signals enter to the voice coil and by interacting of the time varying currents with magnetic field a force on the mirror is derived. The equation of motion is written as:

\[
m \frac{d^2x}{dt^2} + R_m \frac{dx}{dt} + s x = F_0 e^{j \omega t}
\]

(2)

or:

\[
x(t) = F_0 \left( \frac{s}{s - m \omega^2} + \frac{j \omega R_m}{s - m \omega^2} \right) e^{j \omega t},
\]

(3)

where \( s, m, R_m, F_0, \omega \) are stiffness, total mass of the vibrator, mechanical resistance, driving force and modulating frequency, respectively. According to the above equation we can modify the beam movement by \( \tan(\Theta) \) where \( \Theta \) is the angle between incident beam and vibrating mirror. So, by substituting of Eq. (3) into Eq. (1) we found:

\[
\bar{I}[x(t), y, z] = I_0 \frac{w_0^2}{w^2(z)} \int_a^c \int_a^b \exp\left\{ -2\left[ \frac{|x + \tan(\Theta) x(t)|^2}{w_x^2(z)} + \frac{y^2}{w_y^2(z)} \right] \right\} dx dy.
\]

(4)

Displacement of mirror is supposed parallel to the loudspeaker axis. Thus, enough attentiveness must be taken into account in the magnet and cone suspender designing to prevent any distortion. In our approach, only \( x \) component of the Gaussian profile varies during the modulation. Schematic representation of the modulator is illustrated by Fig. 2.

4. DETECTION AND DEMODULATION

A \( pn \) photodiode has been used for direct detection process and its dimensions should be smaller than that of the linear part, which is described in Section 2 (see Fig. 1). The detector should keep at center of the linear section to sense the fluctuation of intensity well. Effective boundaries of a practical photodiode are marked by \( a, b \) and \( c \) (c.f. Fig. 3). The photodiode is sensitive to the average intensity, so by integrating of Eq. (1) over the detector surface area the \( \bar{I}(x, y, z) \) in the steady state will be found:

\[
\bar{I}(x, y, z) = I_0 \frac{w_0^2}{w^2(z)} \int_a^c \int_a^b \exp\left[-2\left(\frac{x^2 + y^2}{w^2}\right)\right] dx dy,
\]

(5)

and by adding a signal:

\[
\bar{I}[x(t), y, z] = I_0 \frac{w_0^2}{w^2(z)} \int_a^c \int_{a + \tan(\Theta)x(t)}^{b + \tan(\Theta)x(t)} \exp\left[-2\left(\frac{x^2 + y^2}{w^2}\right)\right] dx dy.
\]

(6)
The current-voltage (I-V) characteristics of the pn junction follows the equation below:

\[ i^* = i_{sat} \exp\left(\frac{qv}{kT}\right) - i_{ph}, \]  

(7)

where \( q \): electron charge, \( v \): applied voltage, \( k \): Boltzmann constant and \( T \): temperature (Kelvin). \( i_{ph} \) and \( i_{sat} \) are photoinduced and saturation current, respectively. The relation between \( i_{ph} \) and intensity is:

\[ i_{ph} = \frac{\alpha \eta AIq\lambda}{hc}, \]

(8)

so, by inserting of Eq. (6) into Eq. (8) the time dependent photoinduced current is found as:

\[ i_{ph}(t) = \frac{\alpha \eta AI[x(t), y, z]q\lambda}{hc}. \]

(9)

Finally we obtained a relation for time dependent current generated by photodiode:

\[ i(t) = i_{sat} \exp\left(\frac{qv}{kT}\right) - I_0\left[\frac{\alpha \eta AI\lambda w_0^2}{hc} \int_a^{b+tan(\theta)x(t)} \exp\left[-2\left(\frac{x^2 + y^2}{w^2}\right)\right] dx dy\right], \]

(10)

where: \( \lambda \): wavelength of incident photons, \( h \): Plank’s constant, \( c \): velocity of light \( A \): surface area of photodiode \( \alpha \): optical loss factor and \( \eta \): quantum efficiency. Here, the photodiode operates in the third quadrant of its (I-V) characteristic, and plays as a current controller. Therefore, it should be biased with reverse voltage to operate at linear conditions, which is shown in Fig. 4. The magnitude of \( i(t) \) is dependent upon the \( \tan(\theta) \) and the amplitude of the \( x(t) \).

5. MODULATION SPECTRUM

Since in the present method lowest order transverse mode (see Section 2) plays an important role, so Eq. (6) can be rewritten in this form:

\[ |E|^2_{nv}(x(t), y, z) = |E_0|^2 \left( \frac{w_0^2}{w^2(z)} \int_a^{b+tan(\theta)x(t)} \exp\left[-2\left(\frac{x^2 + y^2}{w^2}\right)\right] dx dy\right)^2, \]

(11)

where \( E \) denotes the electric field amplitude. The above equation shows the time evolution of the squared absolute value of the electric field distribution on the \( x-y \) surface with no time dependency in the field. In another words, by comparing to the conventional modulation types, signals are not affected the carrier frequency and we can say that no bandwidth is required for IPM based communication system. It should be mentioned here that the Doppler shift due to back and forth movement of the beam causes line broadening, but the resultant bandwidth does not contain any information.

In the free-space optics background radiation from reflected sunlight, stars, planets, and other sources enters the detector to create external noise which combine with the internal detector noise caused by random emissions. So, prevention from the background noise will be a determining factor in performance of the free-space laser communication. For the above reason, we produced a narrowband beam by suitable optical filters to obstruct the background radiation interference. Therefore, the modulation spectral response will be independent from the modulating signal, and the communication system will operate normally in a noisy media by this feature of the method.

*To avoid any interference with intensity formula the symbol \( i \) is used to show the current of the diode.
6. EXPERIMENTAL PROCEDURE

A typical communication device that operates with the IPM technique is developed for analog voice communication. A diode laser ($\lambda = 630$ nm, $TEM_{00}$, $P < 10$ mW), is provided for carrier source which is biased with high regulated DC power supply. The woofer loudspeaker, which has the best response for frequencies in the range of 50 Hz - 4 kHz, was applied for modulator (see Fig. 2).

The amplification of signals performs by analog tone-control preamplifier and power amplifier. To prevent from external audio noise, the modulator was shielded by an acoustic insulator. Signals which interfere with natural resonance frequency of the loudspeaker are sources of the amplitude distortion, so the tone-control preamplifier can be used to balance the unwanted components of signal. Fig. 5 shows the operation of a typical communication system based upon the present method. The amplitude of signals should be controlled for limiting the beam displacement. When the improper amplitudes were used, they were caused beam jumping and harmonic distortion. The later arises from the effect of the error function which appears in Eq. (10). On the other hands, if the amplitude of input to be spread over the width of the linear part the shape of the output in the receiver will be deformed, which Fig. 6 shows this fact. Signals were detected directly by the $pn$ photodiode and output currents could be amplified by the same set of the modulator amplifier.

In our experiment, maximum distance of the detector has been located 1Km far away from the transmitter. The system performance of analog link is expressed in terms of the fidelity of the source input signal compared to the destination output signal as measured by mean square error, peak power, FFT or some other suitable criterion. So, to have an evidence of the IPM operation, FFT spectrum of sample signals\(^\dagger\) after demodulating has been shown in Fig. 7a. The calculated spectrum is found by Eq. (10) (see Fig. 7a), and our experimental results are given by Fig. 7b. FFT simulation is performed with Matlab and Maple Release softwares\(^1\).\(^2\),\(^3\) and the experimental data have been obtained by Tektronix (TDS 210) digital oscilloscope.

7. CONCLUSIONS AND RESULTS

The IPM method for FSLC system is based on the intensity linearity of $TEM_{00}$ mode for one-half of the laser beam. By such a technique, we modulated the audio signals in the form of speech properly and experimental results are in good agreement with theoretical predictions coming from the Gaussian profile. Some of the advantages of the method are low cost, flexibility, high fidelity and better performance of the detector.

Variation of atmospheric conditions at far distances will cause a sever distortion. So, we need stability conditions of the intensity profile for distortionless communication. Therefore, it seems that the method can be applied for short and medium distances due to low deformation of the profile.\(^4\) In order to the frequency dependency of the term $((s - mw^2) + jwR_{m})$, the amplitude of demodulated signals fluctuates by frequency discrimination effect. To avoid any problem, the tone control preamplifier has an important responsibility to balance the gain of the output signals before the modulator.

Transmission may be distorted by undulation of the atmosphere refractive index at hard air-flow and causes other case of perturbation. The suggested solutions are discussed as: I-Double beam configuration and II- Using a sub-carrier. If we were used another laser beam, which contains noise only, they could be locked in the amplifier by another detector at the opposite phase to cancel undesired noise. In the second procedure, before the modulator the sub-carrier of frequency more than the noise level carries the information. As a technical feasibility, IPM can be extended to the higher modulation rates by acoustooptic modulators for digital communication,\(^5\) where it is our goal. Our emphasis here that a new concept of FSLC and other related areas may be developed by such an acoustooptic device.

ACKNOWLEDGMENTS

We wish to acknowledge the Department of Electrical and Electronic Engineering of the Shiraz University for laboratory support of the present work.

\(^\dagger\)The input information in the modulator were normal sinusoidal signals produced by a function generator.
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Figure 1. Linear fitting on the Gaussian function for a circular beam of 1cm spot size.

Figure 2. Modulator components are (1) guide mirrors, (2) woofer loudspeaker, (4) vibrating mirror, (5) laser beam at $TEM_{00}$ mode, (6) loudspeaker input connectors. The optimum angle between beam and vertical axis of the vibrating mirror is $45^\circ$. 
Figure 3. The scheme of a typical pn photodiode is shown.

Figure 4. Current - Voltage curve of the pn photodiode.
Figure 5. The operation of a typical analog voice communication system is illustrated.

Figure 6. The improper amplitude distorts the shape of the output signal. The dash-dot line is a perturbed signal and the solid line will be the unchanged sinusoidal signal.
Figure 7. FFT spectrum of the four sinusoidal signals after demodulating are shown both theoretically (a), and experimentally (b).