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SENSITIVITY ANALYSIS OF AN $HG_{1-X}CD_XTE$ BASED PHOTOCONDUCTIVE RECEIVER FOR LONG WAVELENGTH FREE SPACE OPTICAL COMMUNICATION AT 9.6 MM

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Abstract

In this paper we examine theoretically the performance of an optical receiver based on an $Hg_{0.77}Cd_{0.23}Te$ photoconductive detector for its possible application at 9.6 µm free space optical communication system at moderate bit rates. A rigorous noise model of the receiver has been developed for this purpose by incorporating all significant sources of noise. Our analysis reveals that the photoconductive receiver exhibits sensitivity of -50 dBm at a bit rate of 100 Mb/s and -45 dBm at a bit rate of 1Gb/s and total mean-square noise current $\left\langle i_n^2 \right\rangle = 10^{-14}$ A^2 at a bit rate of 100 Mb/s and $\left\langle i_n^2 \right\rangle = 10^{-13}$ A^2 at bit rate of 1 Gb/s for a photoconductor gain of 9.3 and 3-dB bandwidth of 120 MHz. The photoconductive optical receiver has a flat frequency response and it exhibits a transimpedance gain> 56 dB-Ohm at moderate bit rates.

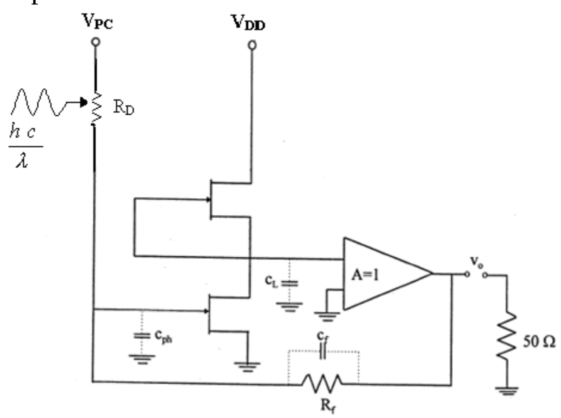
I. INTRODUCTION

The optical wireless (IR) technology [1-2] seems to be ideal for free space optical communication or optical wireless communication systems of the future. The photoconductors have been employed in numerous photodetection applications because of their simplicity and their high sensitivity arising out of gain for the detection of weak optical signals [3-4]. In other applications where speed is more important, photovoltaic detectors of lower sensitivity are generally deployed. Intrinsic photoconductors have very high light absorption coefficient (10^5 to 10^7 m^{-1}), so that dimension in the direction of light incidence need only be a few micrometers. Mercury cadmium telluride (MCT) based detectors can be tailored to the desired wavelength by varying the mole fraction x in $Hg_{1-x}Cd_xTe$ for operation at wavelength from 1µm to 30 µm. The ternary alloy $Hg_{1-x}Cd_xTe$ is also characterized by its extremely high electron peak velocity and mobility. These properties have drawn renewed interest in the study of photoconductors as high speed high sensitivity photodetectors [5-6]. High electron peak velocity ($\approx 5\times10^5$m/s) leads to smaller value of device transit time and therefore to a larger gain-bandwidth product. A large difference between the mobilities of electron ($\approx 10^5$cm^2/V.s) to hole (≈ 450cm^2/V.s) on the other hand leads to a large intrinsic signal gain. Sensitivity analysis of an $Hg_{1-x}Cd_xTe$ based photovoltaic receiver for long-wavelength free space optical communication systems has been theoretically examined by Dwivedi et. al. [7] but sensitivity analysis of photoconductive receiver based on $Hg_{1-x}Cd_xTe$ for free space optical communication system is yet to be examined. Following the treatment of Personick [8] and Forrest [3], we calculate the receiver sensitivity for the case of photoconductive detectors. This response to a square optical input pulse has been found to be common to all $Hg_{1-x}Cd_xTe$ photoconductors as well as photoconductors made from other materials [9], and is therefore of interest in this treatment. In this paper we examine theoretically the performance of front-end circuit of photoconductive detector based on HgCdTe/MESFET optical receiver for possible application at 9.6µm free space optical communication system at a bit rate of the order of hundreds of Mb/s. A rigorous model of the receiver has been developed for computation of noise, sensitivity and transimpedance gain and hence frequency response of the front-end receiver circuit.

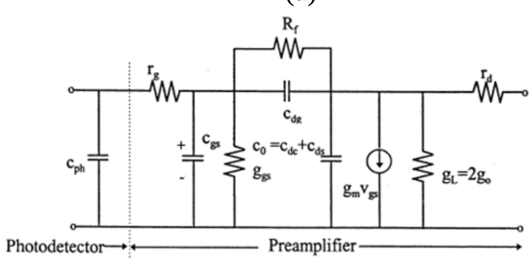
II. THE RECEIVER CONFIGURATION

The proposed optical receiver consists of an HgCdTe based photoconductive detector at the input followed by a MESFET pre-amplifier stage used in the common-source mode. The amplifier works in the transimpedance mode. The schematic circuit diagram of the receiver is shown in Fig. 1a. The output of the preamplifier stage is fed to a unity voltage gain buffer stage having negligible input conductance. The voltage follower stage enables one to transform the voltage at the desired 50 Ω level at the output for processing the detected signal. The MESFET pre-amplifier stage has been dynamically loaded with the help of an identical MESFET which sinks the drain current. The effective load resistance in this case is determined by the reciprocal of the dynamic output conductance (g_0) of the MESFET acting as the dynamic load. In Fig. 1a various capacitances that are needed to be considered for the a.c. analysis are shown by dotted lines.

These include the capacitance c_L representing the total capacitance across the load resistor, c_{ph} representing the capacitance of the photoconductive detector and c_f representing the required capacitance across R_f in order to obtain maximally flat frequency response of the amplifier.



(a)



(b)

Fig.1 (a) Schematic circuit diagram of the HgCdTe based Photoconductor/MESFET optical receiver, (b) equivalent small signal circuit diagram of the HgCdTe based Photoconductor /MESFET optical receiver

The small signal equivalent circuit of the basic MESFET component for the dark condition has been used in the present analysis. The small-signal equivalent circuit of the amplifier used in the analysis is shown in Fig.1 (b). In this small-signal model input resistance has been assumed to be negligible. This is true when the MESFET channel is moderately doped. For sake of simplicity, the source contact resistance has also been ignored. The small signal equivalent circuit parameters of the MESFET used in the receiver model [10] include gate-to-source capacitance, c_{gs}, gate-to-drain capacitance, c_{dg}, the drain-to-source capacitance, c_{ds}, the channel capacitance, c_{dc}, the transconductance, g_m and the output conductance, g_0. In the equivalent circuit, g_{gs} has been shown as the input conductance of the MESFET. The output capacitance c_0 shown in the equivalent circuit consists of the drain-to-source capacitance and the channel capacitance. In the small signal equivalent model g_L is the output load conductance which is the equivalent of the output effective conductance of the MESFET used as the amplifier and that used for dynamic loading.

The transimpedance gain Z_T of the photoconductive detector/MESFET optical receiver can be expressed in terms of device and system admittance parameters [10] as

$$Z_T \cong \frac{-\beta_0^{'}/g_L^{'}}{\left(1+j2\pi f\beta_0^{'}\tau^{'}\right)\left(1+j2\pi f\tau_L\right)+j2\pi f\tau_{dg}} \qquad (1)$$

where $\beta_0^{'} = \frac{g_m}{g_f}$ (2)

$$g_L^{'} = g_L + g_0 = 2g_0 \qquad (3)$$

$$\tau^{'} = \frac{\left(c_{gs}+c_{dg}+c_{ph}\right)}{g_m} + c_{dg}r_d \qquad (4)$$

$$\tau_L = \frac{\left(c_{dg}+c_{ds}+c_{dc}\right)}{g_L^{'}} \qquad (5)$$

and $\tau_{dg} = \frac{\beta_0^{'}c_{dg}}{g_L^{'}}$ (6)

Here c_{gs} is the gate-to-source capacitance, c_{dc} channel capacitance, c_{ds} is the source-to-drain capacitance, c_{dg} is the gate-to-drain capacitance, g_m is the transconductance of the device, r_d is the drain contact resistance, g_L is the output load conductance of MESFET and g_0 is the conductance of the MESFET preamplifier [11].The denominator of Equation (1) can be rearranged to identify the following pole frequencies

$$f_1 = \frac{1}{2\pi\left(\beta_0^{'}\tau^{'}+\tau_{dg}+\tau_L\right)} \text{ and}$$

$$f_2 = \frac{\left(\beta_0^{'}\tau^{'}+\tau_{dg}+\tau_L\right)}{2\pi\left(\beta_0^{'}\tau^{'}\tau_L\right)} \qquad (7)$$

With the application of feedback resistance R_f and assuming that $c_L / g_L^{'} = R_f c_f$, the transimpedance gain can be expressed as

$$Z_{Tf} = \frac{Z_{Tf0}}{1-\left(f^2/f_0^2\right)+\left(j/Q_0\right)\left(f/f_0\right)} \tag{8}$$

where $$Z_{Tf0} = \frac{-\beta_0'/g_L'}{1+\left(\beta_0' g_f/g_L'\right)} \tag{9}$$

$$Q_0 = \frac{f_0}{f_1+f_2} \tag{10}$$

and $$f_0 = \sqrt{f_1 f_2\left(1+\beta_0' \frac{g_f}{g_L}\right)} \tag{11}$$

III. SIGNAL WAVEFORMS

The response of a photoconductor is described by a short rise time followed by an exponentially decaying tail of characteristic time τ. The rapid rise is due to the transit time of carriers from cathode to anode and the fall time is determined by the effective recombination time of photogenerated carriers. The response of a typical photoconductor to a bit of duration T_b is, a square current pulse followed by a slow decay. This type of response is accounted for nonlinear processes involving generation resulting from the asymmetry of carrier capture and emission times from deep levels [3, 12]. In computation of signal waveform we have followed reference [3].

IV. PHOTOCONDUCTOR NOISE COMPONENTS

The front-end of the receiver under consideration consists of a photoconductor used in conjunction with a transimpedance amplifier employing a MESFET for the first stage of amplification. We consider different sources of noise for the above receiver circuit. The block diagram of the receiver is shown in Fig 2(a) consisting of detector, preamplifier with transfer function A(f) and an equalizer with transfer function $H_{eq}(f)$. The most significant sources of noise are Johnson noise, photoconductor shot noise due to the recombination of photogenerated carriers via traps in the semiconductor, shot noise due to MESFET gate leakage, channel noise of the front-end MESFET, flicker noise of the MESFET and photoconductor and noise due to intersymbol interference. A noise equivalent input circuit consisting of photodetector and preamplifier is shown in Fig 2(b). In the figure, R_T is the equivalent input resistance consisting of the parallel combination of the photoconductor dark resistance R_D and input resistance of the front-end. In the case of a transimpedance amplifier, the input resistance of the front-end is replaced by the feedback resistance R_f. Also shown in the equivalent circuit is the signal photocurrent generator I_p , a mean square noise-current generator, $\langle i_n^2\rangle$, and an average mean square series-noise voltage generator, $\langle e_n^2\rangle$, due to the MESFET channel noise. For the circuit under consideration, we assume that the front-end and photoconductive resistances are equal, $R_f = R_D = 2R_T$ (i.e., matched). The values of mean square Johnson- noise current, channel shot noise current, MESFET gate leakage shot noise current, MESFET channel noise current, 1/f noise current and current due to Intersymbol interference have been computed as in reference [3]

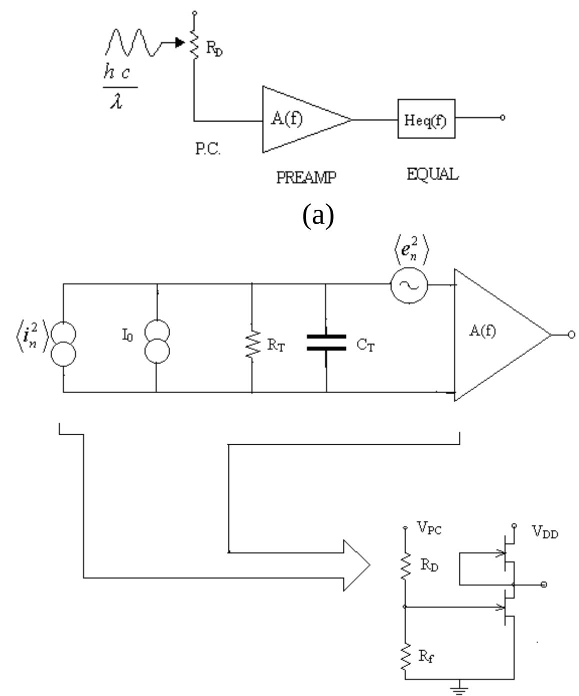


Fig.2 (a) Block diagram of linear receiver channel employing a photo- conductive detector, and (b) photoconductor and preamplifier equivalent circuit for noise equivalent model of the proposed optical receiver.

The mean square value the total signal independent noise current is [3]

$$\langle i_x{}^2\rangle = \langle i_j{}^2\rangle + \langle i_c{}^2\rangle + \langle i_{1/f}{}^2\rangle + \langle i_g{}^2\rangle \tag{12}$$

V. SENSITIVITY OF THE PHOTOCONDUCTIVE RECEIVER

The receiver sensitivity is the minimum amount of optical power required to achieve a specific receiver performance. We now calculate the minimum optical power [3] required for the detection of a data bit with a maximum specified error rate. If the threshold current for the detection of a "0" or "1" during the decision interval is denoted as D, then we define the parameter Q as

$$Q = \frac{D - i}{\left\langle i_n^2 \right\rangle^{1/2}} \tag{13}$$

where i is the signal current during the transmission of either a '1' (i_1) or a '0'(i_0) and $\left\langle i_n^2 \right\rangle^{1/2}$ is the total rms noise consisting of the noise terms listed above. The minimum detectable signal power ($\eta\overline{P}$) of the photoconductor receiver at a given BER or receiver sensitivity, can be obtained as [3]

$$\eta\overline{P} = Q\left(\frac{hc}{q\lambda}\right)\frac{1}{G}\left[\left\langle i_x^2 \right\rangle + 16q^2Q^2G^2I_{ISI}\left(I_{ISI} - I_1\right)\right]^{1/2} + 2\left(\frac{hc}{q\lambda}\right)Q^2\left(2I_{ISI} - I_1\right)B \tag{14}$$

where η is the quantum efficiency. The sensitivity of the photoconductive receiver can be calculated using the above equation for given value of η.

VI. RESULTS AND DISCUSSIONS

Numerical computation has been carried out for an HgCdTe photoconductive detector/MESFET preamplifier front end. Various parameters used in the computation are listed in Table-1.

Results of numerical computation show that this receiver has transimpedance gain >56 dB-ohm at all bit rates for a feedback resistance of $R_f = R_D = 57.88\Omega$ over the entire bandwidth (120 MHz) of the photoconductive detector. Fig.3 shows the variation of mean square value of various noise components with the operating bit rate. The results obtained on the basis of our model reveals that Johnson noise dominates over the other components of the noise up to bit rates of the order of several Gbps. It is found that the mean square value of the total noise current of the photoconductive receiver is dominated at all bit rates B< 1 Gb/s by Johnson noise in the conductive channel. At bit rates ~ 10 Gb/s and above, the mean square value of MESFET channel noise current is found to override the Johnson noise current.

Fig.4 shows the variation of the sensitivity (in dBm) of the receiver with the operating bit rate.It is seen that the photoconductive receiver exhibits a sensitivity of -50 dBm at a bit rate of 100 Mb/s and -45 dBm at a bit rate of 1Gb/s and total mean-square noise current $\left\langle i_n^2 \right\rangle = 10^{-14}$ A^2 at a bit rate of 100 Mb/s and $\left\langle i_n^2 \right\rangle = 10^{-13}$ A^2 at bit rate of 1 Gb/s for a bit error rate (BER)=10^{-9}.The photoconductor gain has been taken as 9.3 for the computation.

In Fig.5 the sensitivity of the receiver has been plotted as a function of bit rate for several values of photoconductive dark resistances, assuming a gain of 9.3. The dominance of Johnson noise is apparent from increase in the sensitivity with increase in channel resistance over the entire bit rate range considered. From Fig.5 it is seen that we can get an improvement in sensitivity of 5 dBm by increasing channel resistance from R_D=57.88Ω to R_D=500 Ω. Thus we can get better sensitivity by increasing the channel resistance of the detector because Johnson noise reduces by increasing the channel resistance of photoconductive channel. But channel resistance is not a free parameter which can be arbitrarily increased in a photoconducting channel without affecting other parameters.

The resistance depends on the doping of the channel material which for our discussion is $Hg_{0.77}Cd_{0.23}Te$, and on channel geometry. Due to very high mobility and peak velocity characteristic of this material, photoconductors can have a relatively high gain-bandwidth product. The high mobility, however, also implies a high conductivity, and therefore Johnson noise limits receiver sensitivity unless the number of free carriers can be sufficiently reduced. An alternative means of decreasing carrier concentration is to compensate the donors in HgCdTe using a deep acceptor levels as can be induced by addition of ion into the channel [3].

The Johnson noise current can be reduced by increasing channel resistance if we decrease the channel thickness *t*. However, reduction of *t* causes quantum efficiency of the device to fall resulting in incomplete optical absorption of the signal by thin absorbing channel. It has been found that for $N_D=10^{21}/m^3$,$N_A=1.87\times10^{16}/m^3$ and device dimensions *l*=50μm, *w*=50μm and *t*=10μm we obtain maximum channel resistance of R_D=57.88Ω.If we change thickness from *t*=10μm to *t*=1μm we get R_D=578.8Ω which improves sensitivity nearly 5dBm.Thus optimizing the device geometry in respect of quantum efficiency, responsivity and detectivity we can improve the sensitivity of the optical receiver.

Table-1 Parameters used in the computation

Parameter	Value
I_g (Gate leakage current)	50(nA)
g_m (MESFET transconductance)	30(mS)
Γ (Noise figure)	1.1
C_T (total capacitance of receiver-photo-detector front-end cicuit)	1.0(pF)
f_c (Corner frequency)	20(MHz)
c_{gs} (gate-to-source capacitance)	18.5 fF
c_{dg} (gate-to-drain capacitance)	3 fF
g_0 (MESFET conductance)	1.3 mS
r_g (gate contact resistance)	10Ω
r_d (drain contact resistance)	10Ω
c_L(total capacitance across load resistor)	4.5fF
`I_1 (Personick Integral)	0.6574
I_2 (Personick Integral)	0.8852
I_f (Personick Integrals)	0.3958
I_3 (Personick Integral)	0.2507
I_{ISI} (Personick Integral)	0.7296
c_{ph} (detector capacitance)	5.53fF
R_D (detector resistance)	57.88Ω[13]
G (photoconductor gain)	9.3[13]
τ (minority charge carrier life time of photoconductor)	1.33ns[13]

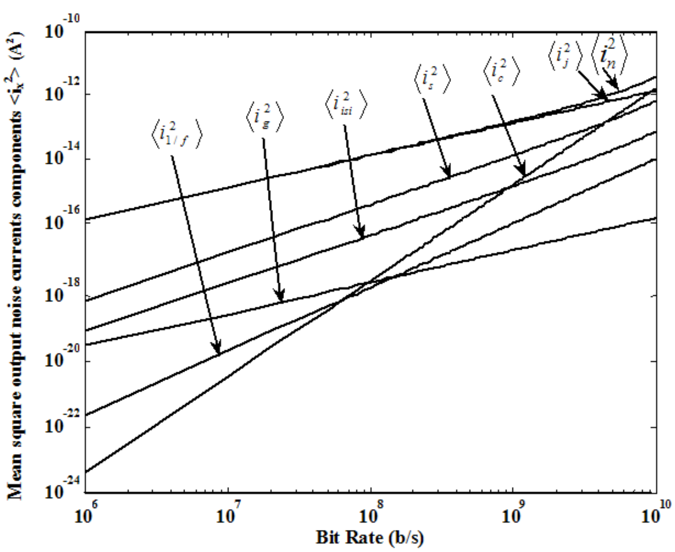


Fig.3 Noise current variation with the Bit rate of the receiver (at an operating wavelength of 9.6µm)

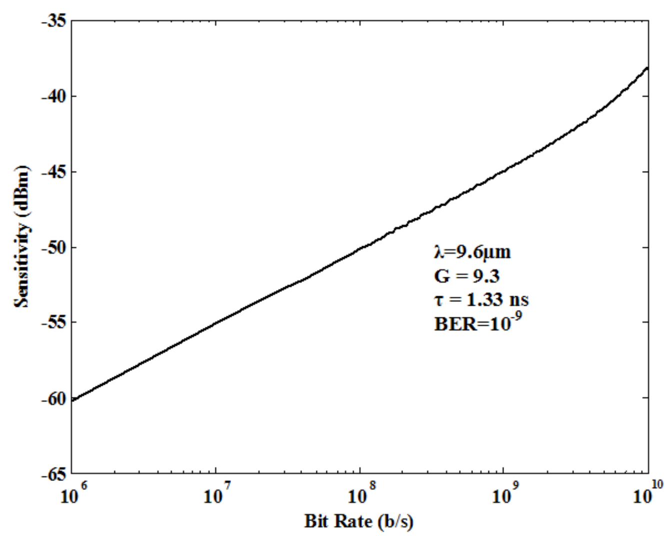


Fig.4 Sensitivity variation with the Bit rate of the receiver (at an operating wavelength of 9.6µm)

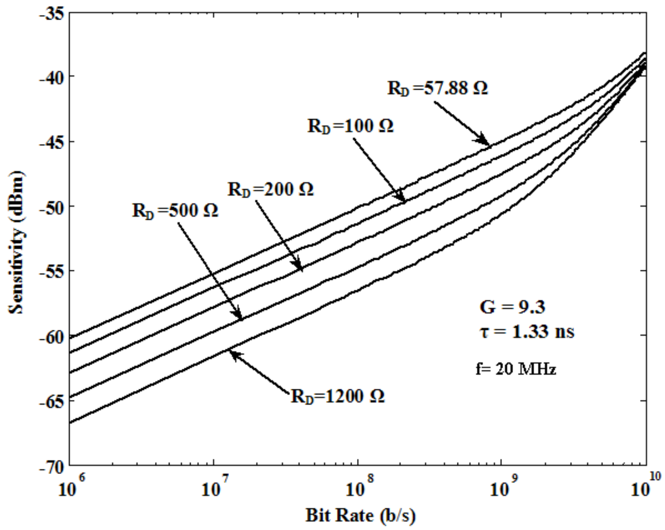


Fig 5 Photoconductive receiver Sensitivity versus Bit rate for several values of channel resistance R_D.

VII. CONCLUSIONS

We have computed different noise components and total noise and sensitivity of a photoconductive receiver for use in moderate bit rate for free space optical communication systems. Sensitivity of the proposed receiver has been found to be limited by Johnson noise resulting from the low resistance of the conducting channel at all bit rates <1Gb/s. At higher bit rate MESFET channel noise is found to dominate. We also find that the sensitivity of the receiver increases at all bit rates as channel resistance of the photoconductive detector increases. It is found from the frequency response of the receiver that transimpedance gain is >56dB-ohm at all bit rates of interest. Although the potential sensitivity advantage projected by this analysis is limited by gain-bandwidth product of photoconductive detector, the simplicity of photoconductive detector makes it attractive in applications where the circuit complexity and sensitivity degradation associated with equalization are not considered important. We conclude that an HgCdTe based photoconductive receiver is suitable for its possible application at 9.6 µm free space optical communication system at moderate bit rate.

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