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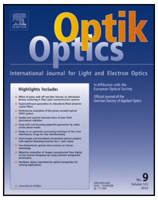

On the research of avalanche photodiodes-based heterodyne in FM/cw laser rangefinder

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ABSTRACT

An avalanche photodiodes (APDs)-based heterodyne technique for FM/cw laser rangefinder (FM/cw LRF) is described. Based on a modified APDs model, the properties of heterodyne are theoretically analyzed and experimentally demonstrated under different illumination intensities and multiplications, both the amplitude and the signal to noise ratio (SNR) of the difference frequency signal are inversely proportional to the unmultiplied current at a high multiplication and are proportional to the square of multiplication at a low multiplication.

1. Introduction

FM/cw LRF (frequency modulation/continuous wave laser range finder) has the advantage of not having blind range zone over pulsed LRF and not having range ambiguity over phase-shift LRF. The realization of the receiver in a FM/cw LRF can be of two types, the traditional low noise amplifier (LNA) plus mixer type and the heterodyne type where photoelectric detector works as a photoelectric mixer. When used for a complicated application such as scannerless 3D imaging laser radar [1], heterodyne must be adopted for realizing composite architecture and stronger immunity to adjacent coupled interference [2].

The photoelectric detectors that can be used as a photoelectric mixer must have their responsivities vary with applied bias. Quantum well electro-optic reflectance modulator (QWEO), voltage-modulated optical detector (VMOD) and metal semiconductor metal detector (MSM) have all been tried to realize heterodyne but ether suffer from the difficulties in bias modulation or the extremely low responsivities [3,4] while APDs have shown a promising prospect due to the bias-sensitive responsivity[5]. Another question that constraints the FM/cw LRF is the output power of continuous-wave (cw) lasers used in FM/cw LRF is limited due to the heating effect (therefore can only achieve a maximum average output power of no more than a hundred watt), which leads to a poor performance of FM/cw LRF under sunlight [6]. To reveal the influences of illumination intensities on FM/cw LRF, David Dupuy has analyzed the problems using the APD's Miller empirical model and considered that the poor performances of the APD-based photoelectric mixer are mainly determined by the concavity index of the APDs [7–9], however, this is lack of evidence as the concavity index of the APDs is not seriously influenced by the illumination intensities [10]. In this letter, based on a modified APDs model, we study the properties of APDs-based heterodyne under different illumination intensities to optimize the performance of FM/cw LRF.

2. Theoretical analysis

2.1. The principle of FM/cw LRF

The block diagram of a FM/cw LRF with a heterodyne receiver is shown in Fig. 1 where both the output and hence the received

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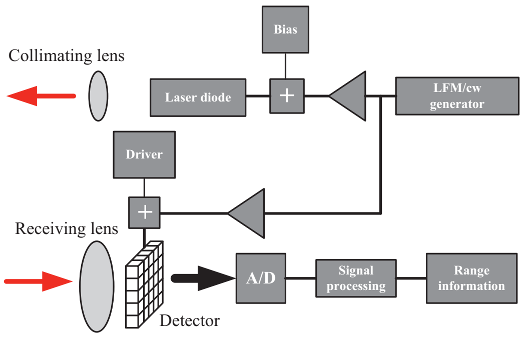

Fig. 1. FM/cw LRF block diagram.

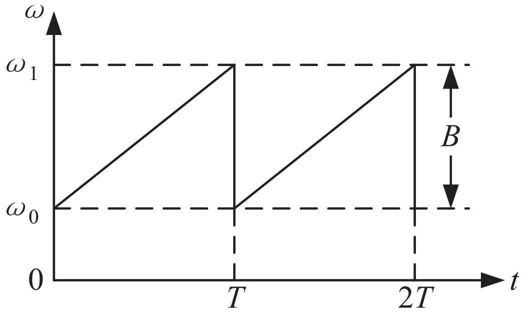

Fig. 2. The time–frequency relations in FM/cw signal.

power of laser $P_R(t)$ and the bias of detector $V_{LO}(t)$ are modulated with a FM/cw signal shown in Fig. 2.

$$P_R(t) = P_0\left\{1 + m_P \cos\left[\omega_0(t-\tau) + \pi k(t-\tau)^2\right]\right\} \tag{1}$$

$$V_{LO}(t) = V_R\left[1 + m_V \cos\left(\omega_0 t + \pi k t^2\right)\right] \tag{2}$$

where P_0, V_{LO} are average received power and bias, respectively. m_P, m_V are the modulation indexes of laser power and bias, respectively. τ is the delay of the received signal due to the round trip of the light. ω_0 is the start angular oscillation frequency of FM/cw signal and k the modulation slope defined as

$$k = \frac{B}{T} \tag{3}$$

where B is the bandwidth of FM/cw signal and T the period of the signal.

If by some means, the responsivity of the detector varies linearly with bias, the filtered mixed signal (the difference frequency signal) can be expressed as

$$I_{IF}(t) = \frac{1}{2}k_R R_0 P_0 V_R m_P m_V \cos(2\pi k \tau t) \tag{4}$$

where k_R represents the linear relations between bias and responsivity, R_0 is the spectral responsivity. Calculate the frequency of $I_{IF}(t)$, f_{IF}, and the target range is given by

$$R = \frac{c}{2k} f_{IF} \tag{5}$$

where c is the speed of light.

2.2. The modified APDs model

When working under a low light illumination, the multiplication of APDs with bias before breakdown can be described using the Miller empirical model [10].

$$M = \frac{I}{I_P} = \frac{1}{1-(V_J/V_B)^n} \tag{6}$$

where I and I_P are the multiplied and un-multiplied current respectively; V_J is the voltage across APDs' multiplication area and V_B the breakdown voltage. n is the parameter determined by material, doping profile, and optical wavelength.

Miller empirical model cannot effectively describe the multiplication of APDs under a high light illumination due to the effects of the series load and space charge effect [11,12], therefore, a modified APDs model is given as [10]

$$M_{mod} = \frac{1}{1-[(V_J - IR_S)/V_B]^n} \tag{7}$$

where R_S is the effective series resistance containing the series load and the space charge effect.

2.3. APDs-based heterodyne

When working as a photoelectric mixer, the voltage across APDs' multiplication area is modulated by FM/cw signal shown in Eq. (2), and this turns M_{mod} to be

$$M_{mod}(t) = \frac{1}{1-[(V_R + V_R m_V \cos(\omega_0 t + \pi k t^2) - IR_S)/V_B]^n} \tag{8}$$

when $V_R m_V << (V_R - IR_S)$, Eq. (8) can be approximated to be

$$M_{mod}(t) \approx M_0 + K_0 V_R m_V \cos\left(\omega_0 t + \pi k t^2\right) \tag{9}$$

where

(10a)$M_0 = \frac{1}{1-[(V_R - IR_S)/V_B]^n}$

(10b)$K_0 = \frac{anM_0^2(aV_R - bM_0)^{n-1}}{1+bnM_0^2(aV_R - bM_0)^{n-1}}$ where $a = 1/V_B$ and $b = I_P R_S/V_B$

As the received power of laser is shown in Eq. (1), the output current from APDs is

$$\begin{aligned} I(t) &= P_R(t) \times M_{mod}(t) \times R_0 \\ &= R_0 \times \left[M_0 + K_0 V_R m_V \cos\left(\omega_0 t + \pi k t^2\right)\right] \times \left\{P_0 + P_0 m_P \cos\left[\omega_0(t-\tau) + \pi k (t-\tau)^2\right]\right\} \end{aligned} \tag{11}$$

and the amplitude of the difference frequency signal is

$$I_{IF}(t) = \frac{K_0 P_0 m_P V_R m_V R_0}{2} \tag{12}$$

While, the mean-square shot-noise current of APDs is given by

$$\left\langle I_N^2 \right\rangle = 2qI_P M_0^2 F(M_0) B_{AMP} \tag{13}$$

where $F(M_0)$ is the excess noise factor, B_{AMP} is the bandwidth of intermediate frequency amplifier and q the electron charge. Therefore, the SNR of the difference frequency signal can be written as

$$\begin{aligned} \mathrm{SNR} &= \frac{I_{IF}^2(t)}{2\left\langle I_N^2\right\rangle} = \frac{P_0^2 m_P^2 V_R^2 m_V^2 R_0^2}{16qI_P M_0^2 F(M_0) B_{AMP}} K_0^2 \\ &= \frac{P_0^2 m_P^2 V_R^2 m_V^2 R_0^2}{16qI_P M_0^2 F(M_0) B_{AMP}} \cdot \left(\frac{anM_0^2(aV_R - bM_0)^{n-1}}{1+bnM_0^2(aV_R - bM_0)^{n-1}}\right)^2 \end{aligned} \tag{14}$$

When at a low multiplication, the term $bnM_0^2(aV_R - bM_0)^{n-1}$ trends to be 0 and SNR trends to be proportional to M_0^2 and inversely proportional to I_p, while when at a high multiplication, k trends to be a/b and

$$\mathrm{SNR} \rightarrow \frac{P_0^2 m_P^2 V_R^2 m_V^2 R_0^2}{16qI_P^3 R_S^2 M_0^2 F(M_0) B_{AMP}} \tag{15}$$