Analysis of Optimum Heterodyne Receivers for Coherent Lidar Applications

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ABSTRACT

A full analysis of the combined effects of all the noise sources of optical heterodyne receiver and the interaction between the competing control parameters of the receiver detector and pre-amplifier will be presented. This analysis provides the mean for true optimization of the coherent lidar receiver. The significance of the optimization of heterodyne receiver is shown for 2-micron coherent lidar.

INTRODUCTION

Coherent lidar has proven to be a powerful tool for a wide range of remote sensing applications capable of measuring atmospheric wind velocity, turbulence, aerosol concentration, cloud height and velocity, and detection of atmospheric constituents and pollutants. Many coherent lidar applications, particularly airborne and space-based applications, impose stringent power and size constraints while requiring high levels of sensitivity. Therefore, optimization of the lidar heterodyne photoreciever is one of the critical steps in ensuring full utilization of limited resources to achieve the required sensitivity. This paper provides a full analysis for optimization of coherent lidar receiver sensitivity and applies this analysis to 2-micron heterodyne receiver.

Many past works have analyzed the effects of the critical photoreceiver parameters and investigated the optimum optical heterodyne detection. It has been shown that there is an optimum local oscillator power level for which the sensitivity of optical heterodyne receiver reaches its maximum value[1]. More recently a closed-form expression defining the optimum local oscillator (LO) power was derived[2]. The object of this paper is to present a full analysis of the combined effects of the detector non-linearity and capacitance, and the amplifier gain and noise. This analysis allows for quantifying the impact of various detector and pre-amplifier parameters and their interactions, and provides the mean for true optimization of optical heterodyne receiver. The optimization analysis is then applied to 2-micron heterodyne receivers using InGaAs photodiodes. The analysis of 2-micron heterodyne receivers clearly illustrates the improvements resulting from adjusting the key control parameters of the detector and its interfacing amplifier. The significance of reducing the parasitic capacitances associated with the detector and the pre-amplifier is described, and the analytical approach for optimization of the receiver pre-amplifier is explained.

PARASITIC CAPACITANCES

Reducing the capacitances associated with the detector and its interfacing pre-amplifier directly translates to lower total noise power and improved receiver performance. Since the detector junction capacitance is directly proportional to its active area, it is important to select the smallest detector size possible without introducing excess diffraction and aberration loses due to the focusing elements. The other major limiting factors are the detector linearity and system alignment tolerances that will suffer when reducing the detector active area. Once the diameter of the detector active area is specified, the parasitic capacitances associated with the detector and its interface circuits must be addressed.

Minimization of the detector parasitic capacitances has a major impact on the receiver performance. This can be achieved by integrating the detector with its bias circuit and the pre-amplifier on a single chip thus substantially reducing the parasitic capacitances associated with detector package and leads. To evaluate the improvement resulting from the integration of the detector and its interface circuits for 2-micron heterodyne receivers, several InGaAs detector elements were removed from their standard housing. Each detector element was surface-mounted in a microwave SMA package along with its bias circuit and a 50-ohm resistive load. The frequency response of the detectors was measured in a heterodyne detection setup consisting of two tunable CW lasers, a beam combiner, and a series of optical components for routing and conditioning of the laser beams[3]. The frequency response curves were obtained by measuring the heterodyne signal power and normalizing it by the product of the DC currents due to the individual beams while varying the frequency of one of the two lasers. Figure 1 shows the measured frequency response of a re-packaged detector compared with a detector in its standard TO can package. Both detectors are 75 microns in diameter and reverse biased by 4.5 volts. Using the frequency response curves, the capacitances of these two detectors were calculated to be 1.16 pF and 2.5 pF for the re-packaged detector and the detector in its standard package, respectively. This is a significant improvement that can result in 1 to 3 dB higher SNR for receivers with IF bandwidths greater than a few hundred MHz.

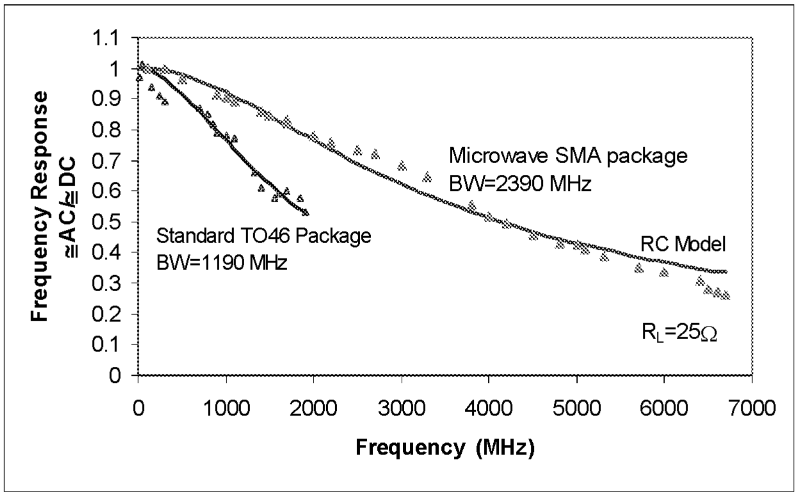

Figure 1. Frequency response of InGaAs photodetector in a Microwave package and in a standard TO package

OPTIMUM AMPLIFIER DESIGN

Optimization of the detector pre-amplifier can be particularly critical for wider bandwidth optical heterodyne receivers. However, conventional amplifier optimization techniques and previous work for optimization of direct detection photoreceivers[4] do not provide the means for determining true optimum amplifier parameters for an optical heterodyne receiver. For a heterodyne receiver, the optimum pre-amplifier parameters and the optimum local oscillator (LO) power are interdependent and cannot be specified individually. This is because of the fact that the optimum LO power is a strong function of the pre-amplifier noise power[2] and therefore related to the pre-amplifier characteristic parameters. Inversely, since the detector shot noise due to the LO is usually the largest receiver noise term, the amplifier optimum design parameters are affected by the LO power level. In this work, an analytical process has been developed to allow for true optimization heterodyne receiver parameters by taking into account the combined effects of the detector and the amplifier characteristic parameters on the receiver performance.

Gain and input capacitance are the two main competing parameters in defining the amplifier optimum design. Higher gain and lower capacitance translates in lower total noise power. However, increasing the amplifier gain will always result in larger capacitance. But by considering the detector capacitance and controlling the amplifier parameters while simultaneously determining the optimum LO power, it is possible to derive at the true optimum performance for a heterodyne receiver. This work uses GaAs MESFET transimpedance amplifier, for interfacing with extended wavelength InGaAs detector, due to its popularity in wideband photoreceivers. However, the analysis presented here can be readily applied to other types of amplifiers.

For a FET amplifier, the main control parameter is its gate width, which determines the amplifier open loop gain and all the intrinsic capacitances and resistances. Using a commonly used MESFET model[5] and the measured parameters of InGaAs detectors, the performance of 2-micron heterodyne receiver was analyzed and its optimum design and operating parameters for different IF bandwidths were determined. Figure 2 is an example of a heterodyne receiver performance illustrating the dependence of the receiver signal-to-noise ratio on the amplifier FET gate width. For this example, the parameters of the re-packaged detector of Figure 1 are used and the amplifier transimpedance feedback is adjusted to provide a 2 GHz IF bandwidth. Figure 2 also shows the corresponding optimum LO power and the amplifier feedback resistor.

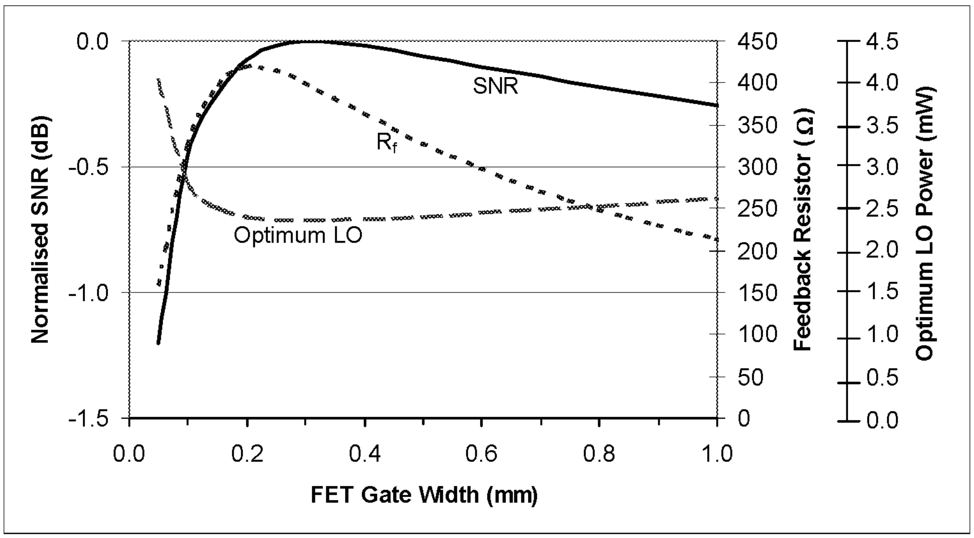

Figure 2. 2-micron heterodyne receiver performance as a function of amplifier FET gate width.

As can be seen from Figure 2, there is an optimum gate width that produces the highest SNR. For this example, the optimum gate width is about 0.3 mm. Previous work has suggested maximizing the amplifier feedback resistor to determine the gate width for optimum receiver sensitivity[4]. However as can be seen from Figure 2, the maximum R_f value does not necessarily correspond to optimum performance for a heterodyne receiver. This is due to the fact that the LO induced shot noise is a major contributor to the total noise power for a heterodyne receiver. As shown in Figure 3, the optimum LO power and the amplifier gate width both increase with the required IF bandwidth almost in a linear manner. Increased receiver noise power resulting from higher LO power and FET gate width is compensated with higher amplifier loop gain and larger IF signal power.

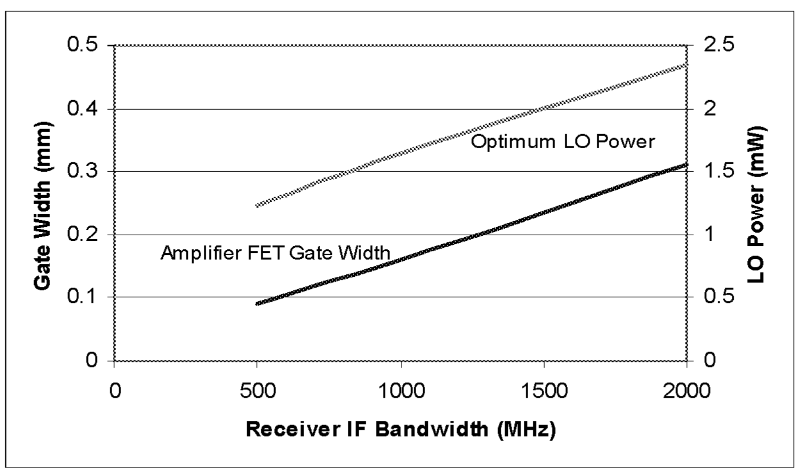

Figure 3. Optimum LO power and amplifier FET gate width versus required IF bandwidth.

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