Ultrafast system enables active remote sensing

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Coherent optical detection is essential to providing with superior range, resolution and sensitivity.

Active optical remote sensing involves illuminating a distant target with a pulsed laser beam. Analyzing the reflected or backscattered optical signal allows us to ascertain its properties, such as location, velocity, material composition, temperature, and stress. The numerous applications of this technique include battlefield target recognition and tracking, atmospheric monitoring, structural monitoring, collision avoidance systems, and terrestrial mapping.

However, the maximum propagation distance in laser detection and ranging (LADAR) as well as optical time domain reflectometry (OTDR) sensors is limited by the resulting signal attenuation. While it is possible to improve the sensor range by increasing the transmitted pulse energy, this is usually accomplished by employing wider laser pulses, which limits the resolution of the target location and the bandwidth of the recoverable information. It is therefore necessary to employ detection mechanisms that can operate satisfactorily at low optical power levels without sacrificing sensor bandwidth. Coherent detection meets this criteria.

Why coherent detection?

Optical sensors are broadly classified into two categories: direct and coherent detectors. Direct detectors are essentially square law devices that are sensitive to the intensity of the received electromagnetic signal. In contrast, coherent detection involves mixing the received signal with an optical local oscillator (LO) in a balanced photodiode to downconvert it to a suitable microwave intermediate frequency (IF). Balanced photodetection suppresses the laser intensity noise and improves the noise figure of the sensor. Coherent detection is a linear process that is sensitive to the amplitude, phase and polarization of the received signal. As a result, information embedded in the signal phase, such as Doppler shifts and vibration signatures, can be recovered easily.

The inherent linearity of coherent detection allows for the translation of mature microwave technology into the optical domain. For example, radio frequency (RF) adaptive filtering following photodetection enables channel equalization, atmospheric turbulence compensation, and efficient background-light filtering. Similar operation in the optical domain would require high Q-factor optical filters, as is necessary for direct-detection sensors. The ratio of the RF powers generated in a coherent link to that in a direct detection link is

$$\frac{P_{\text{opt}, \text{LO}}}{P_{\text{opt}, \text{S}}} = \frac{I_{\text{DC,LO}}}{I_{\text{DC,S}}}$$

where $P_{\text{opt,LO}}$ and $I_{\text{DC,LO}}$ are the optical LO power and the resulting DC photocurrent, respectively. $P_{\text{opt}, \text{S}}$ and $I_{\text{DC,S}}$ similarly characterize the received optical signals. Thus, coherent systems provide shot noise-limited gain by utilizing high LO powers, thereby increasing the sensing range.

High optical power handling ultrafast photodiodes

Due to the availability of high power lasers that can be used as the LO, the coherent gain in practical systems is limited by the power handling capability of the photodiodes. Our InGaAs p-i-n photodiodes exhibit linear behavior for a peak-to-peak pulse output of >2.5V (see Figure 1). The high linearity is due to

Continued on next page
Figure 2. (a) Block diagram of Discovery Semiconductor’s optical coherent system, 'Kitty Hawk.' (b) Sensitivity curves for amplitude and phase modulated communication links. (c) Intermediate frequency spectrum at the balanced photodiode output. NRZ-OOK: Non-return-to-zero on-off keyed. NRZ-DPSK: Non-return-to-zero differential-phase-shift keyed. PRBS: Pseudo-random bit sequence. RF: Radio frequency.

a combination of our proprietary dual-depletion region (DDR) diode structure and optical beam reshaping using graded-index lens coupling. Beam reshaping reduces the peak photocurrent density for a given optical power and can increase the 1dB compression point of the photodiode by ~5dB. This technique is made possible by the top-illuminated geometry of the DDR structure, which allows high current handling and bandwidth exceeding 40GHz. DDR photodiodes have dark currents of the order of few nanoamperes and are commercially available for operation at 0.8µm to 2.2µm wavelength.

Coherent optical system
The most challenging task in implementing a coherent optical system is the generation of a local oscillator signal that tracks the received optical carrier frequency precisely. The linewidth of the resulting IF signal determines the precision with which the optical phase is detected. Our commercially available optical coherent system, 'Kitty Hawk,' based on our proprietary phase locked loop design, can achieve IF linewidth <10Hz (see Figure 2). We have demonstrated amplitude and phase modulated 10Gb/s communication links with record sensitivities of 132 and 72 photons per bit, respectively. This is a testament to the accuracy with which both amplitude and phase can be recovered from a weak optical signal. Preliminary investigations into system performance in the presence of laboratory-induced atmospheric turbulence have proven satisfactory.

Which detector?
It is possible to detect small optical signals using Geiger mode and linear avalanche photodiodes (APD). However, as these are essentially small-signal devices, they are unable to handle large optical signals. In coherent systems, the power can be adjusted according to the received optical power level, and acts as a built-in automatic gain control. As a result, the system presented here has dynamic range and reliability superior to that of its alternatives. Moreover, p-i-n photodiodes are superior to APDs in terms of bandwidth and noise.

Conclusion
The optical coherent system presented here was developed with a focus on the exacting standards of the telecommunications industry. However, it can also serve as the backbone for both free-space and fiber-based remote optical sensors, such as LADAR and OTDR. Faithful recovery of the optical phase will be instrumental in enhancing sensor functionality, including remote vibrometry and polarimetry, allowing better target characterization and identification. Combined with high power handling ultrafast balanced photodiodes, challenging demands on the range and resolution of future remote sensors can be met.

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Continued on next page
References