A novel coherent laser radar architecture based on temporal-diversified optical orthogonal-frequency-division-multiplexing

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INTRODUCTION

Coherent Laser Radar Receiver (CLRR) typically employs high-quality bulk optics to collect and direct light at the photodetector plane. Collection of the back-scattered light from an optically-diffused target requires a large aperture area but it is limited by the atmospheric coherence length. Combining the local laser oscillator (LO) and the received optical signal at the photodetector requires careful optical alignment and good mechanical stability. Alternatively, the collected light can be coupled directly into an optical fiber connect to an optical hybrid that leads to the photodetector. The advantage is that the photodetector and the electronics can be located considerably away from the free-space collecting optics which may have a real-estate constraint. Furthermore, higher speed photodiodes of smaller active areas can be employed to process higher bandwidth signals. However, coupling into a single-mode fiber (SMF) requires high-quality bulk optics and the optical alignment is quite difficult. The coupling loss for SMF is substantially higher than say coupling into a multi-mode fiber (MMF). MMF provides better coupling efficiency and more flexibility in the collecting optics. Furthermore, coupling into MMF is less susceptible to power-fade due to speckle than SMF. Assuming a single focusing lens is used to image the optical beam at the target with a Lambertian surface to an optical fiber, the ratio of the optical power collected into a MMF to that into a SMF without turbulence is given by

$$\beta = \left(\frac{NA_{mm} C_{mm}}{NA_{sm} C_{sm}} \right)^2 , \qquad (1)$$

where NA_{mm} (C_{mm}) and NA_{sm} (C_{sm}) are the numerical apertures (core diameters) of the MMF and SMF, respectively. For typical SMF (MMF), NA_{sm}=0.14 (0.2) and C_{sm}=8.2 (62.5) μm. Therefore, β = 118.6 or 20.7 dB. Commercial available graded index MMF can achieve NA_{mm}=0.29 and C_{mm}=100 μm giving β = 638 or 28 dB. MMF clearly has an advantage in coupling efficiency. In this paper, we propose a novel CLRR digital architecture using optical orthogonal-frequency-division-multiplexing (OFDM) to enable optical coupling into a MMF followed by coherent detection using optical hybrids and balanced photoreceivers[1]. Optical OFDM provides means to potentially correct for multi-path interference (MPI) of the laser radar return signal. OFDM has been extensively used in RF-wireless applications to combat MPI[2]. Furthermore, temporal-diversity using the two orthogonal polarizations of the optical OFDM is proposed to combat fading as a result of atmospheric turbulence. We introduce the concept and core elements of the CLRR architecture followed by a description the DSP algorithm stacks.

COHERENT RECEIVER ARCHITECTURE

The proposed CLRR architecture is shown in Figure 1. Optical OFDM in two orthogonal polarizations (V & H) are synthesized at the transmitter (not shown). The returned optical OFDM signal from the target is collected by receiver optics into a MMF. Adaptive Optics (AO) such as spatial light modulator[3] can be used to transfer light from the MMF into a SMF. Once in the SMF, the light is directed to the dual-polarization coherent receiver consists of a polarization beam splitter followed by a pair of integrated coherent receivers (ICRs)[1]. The received I and Q complex signals of the optical field in each polarization are then digitized and processed to recover the sensor information embedded in the laser radar return signal from the target.

Schematic of the ICR is shown in Figure 2. It consists of an optical hybrid based on lithium niobate waveguide technology and two sets of high-speed balanced photoreceivers integrated in a single compact package[1] as shown in Figure 3. The optical hybrid, consists of four voltage-tunable directional couplers and two electro-optic phase shifters, combines the received optical signal and the LO before coherent mixing at the photodiodes. The four O/E converted I and Q signals from the two ICRs one of each orthogonal polarization (I/V, Q/V, I/H, and Q/H) are then digitized and processed according to algorithms described in the last section.

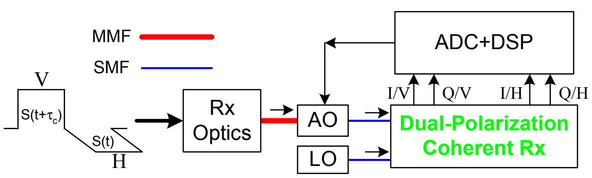

Figure 1. Block diagram of the proposed Rx. ADC: analog-to-digital converter.

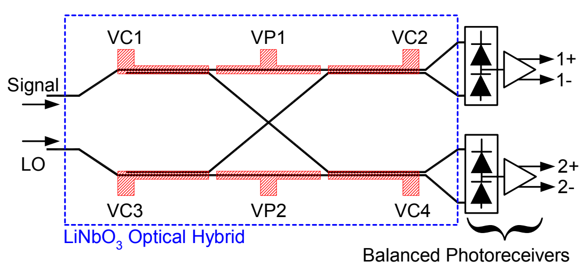

Figure 2. Schematic of an ICR with an optical hybrid and two sets of balanced photoreceivers. VC1 to VC4 are the coupler electrodes while VP1 and VP2 are the phase electrodes.

Generation of optical OFDM at the transmitter is described briefly. The OFDM signal is synthesized via DSP[4] followed by a D/A converter producing electrical I and Q signals. They are then applied to an optical IQ modulator[5] generating the optical OFDM signal, S(t). The two orthogonal polarizations carry the same OFDM information but are time-shifted by an amount commensurate with the atmospheric coherence time, τ_c (~ ms). Figure 4 shows a block diagram of the DSP architecture that synthesizes the required electrical OFDM signal before up-conversion. Details of the DSP architecture will be presented.

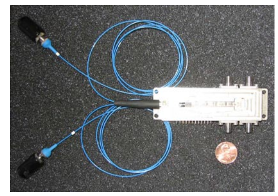

Figure 3. Photograph of the ICR. The ICR package has two input polarization-maintaining fibers for the received optical OFDM and the LO. Dimensions: 127×26×13 mm^3.

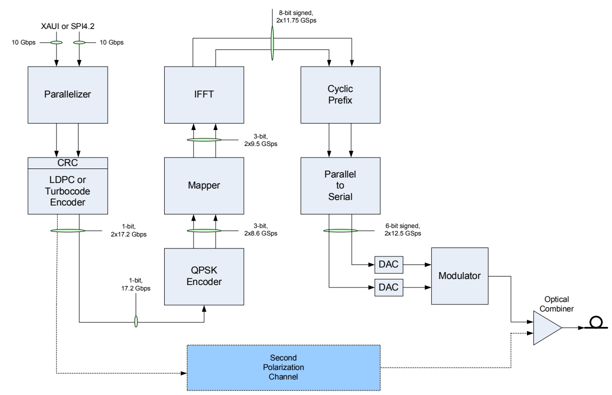

Figure 4. OFDM transmitter DSP architecture.

CONCEPT OF THE PROPOSED CLRR

In this section, we provide a more detail description on the motivation and concept of the proposed receiver. Let us consider the impact of multi-path impairment as a result of atmospheric turbulence and surface roughness and demands to mitigate it. Figure 5 shows a schematic of the optical coupling configuration in the receiver. The multi-path effect can be characterized by the mean distance σ and the spatial coherence length L_c. As a result, the optical field at a given frequency ω in the focal plane of the lens can be represented as a superposition of many phase fronts,

$$E(x,y,\omega) = E_0(\omega)\sum A_i F_i(x,y) e^{j\omega(\Delta L_i / c - t)} \qquad (2)$$

where $E_0(\omega)$ is proportional to the original Fourier amplitude of the signal, A_i is related to the strength of the signal in the i-th path with relative delay ΔL_i, $\sigma^2 = \left\langle \Delta L^2 \right\rangle$, and $F_i(x,y)$ is the field distribution of the diameter *w* with characteristic speckle size equal to the diffraction spot size $\delta \sim f\lambda / D$ where f is the focal distance and D is the collection lens diameter.

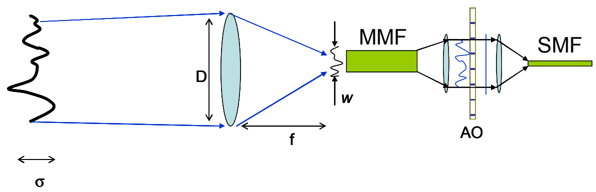

Figure 5. Schematic of the optical coupling stage of the proposed CLRR.

We are now faced with two separate issues – first of all the total field distribution in the focal plane is wide. As a result, it will be difficult to focus all the light into the small core of a SMF. Second, the signal is a composition of many separate signals delayed from each other. Let us consider the impact of multi-path effect. If the bandwidth of the optical signal is $\Delta B << c/3\sigma$ then the maximum group delay $T_{\max} = 3\sigma / c << 1/\Delta B$ indicating that the difference in group delay is not really an issue. The other way to look at it is to see that the maximum phase shift of the RF wave will be $\Delta\varphi_{RF} = 2\pi\Delta B \times 3\sigma / c << \pi$ and thus there will be no destructive interference between the signals reflected from different planes along the axis. Let us assume $\sigma = 100\mu m$ and $\Delta B = 100\,\mathrm{MHz}$ so that $\Delta\varphi_{RF} = 2\pi\Delta B \times 3\sigma / c \sim \pi / 50$. Therefore, the impact of group delay would be relatively insignificant.

Let us return to the first issue that is similar to fading in RF-wireless but with a huge difference: In RF communications the antenna size is significantly smaller than the characteristic "speckle" size of at least few wavelengths – and not all the radiation is collected. In optics, however, the equivalent approach would be to simply use a SMF with an aperture more or less matched to the diffraction spot and then simply collect a small fraction of radiation. But the coupling loss is quite high. Therefore, it is desirable to use MMF and collect as much light as possible. Here we essentially have interference of a collection of speckle patterns from different paths that are not really related to each other. For as long as the mean phase difference between the speckle patterns stays small the sum pattern does not change at all. Therefore, we have a well defined total speckle pattern to be focused into a MMF. As pointed out earlier, MMF can collect about 100 times more light than SMF without turbulence. At the output of a MMF we shall have yet another irregular multi-mode speckle pattern. This speckle pattern, however, can be focused into the SMF using adaptive optics (AO) as can be seen in Figure 5. Note that a 100-fold improvement assumes that w – the size of the focal pattern is actually larger than 62μm –i.e. under the worst conditions. If conditions are better than that the improvement will not be that dramatic. Therefore, using MMF and AO we can get most of the optical power into the SMF. For sensing applications that requires detection of minute optical phase shift (<< mrad), the optical OFDM plays an important role for the DSP algorithm to extract the small phase shift signal. The optical OFDM provides a mean for the DSP to quantify the multi-path effect as a result of the hard target and the atmosphere. This information is used to train the algorithm. The trained algorithm can then be used to compensate for the multi-path-induced noise and ultimately recovers the desirable small optical shift which has a signature that is known a priori. Furthermore, the optical OFDM signal provides the DSP algorithm critical feedback information in order to close the control loop for the AO.

DSP ALGORITHM STACKS

A unified layered architecture for fieldable digital coherent interferometric communications and sensing is depicted in Figure 6. The layered architecture is based on two integrated optical components that enable the embodiment of a generalized transponder consisting of *Synthesizer* and *Analyzer* constructs each consisting of three layers: (i) An Optical layer, composed of an integrated *Quadrature Modulator* and a *Homodyne Receiver* that performs the *linear transformation* of coherent optical signals to/from electrical base-band; (ii) Stabilization layer that maintains the optical components at an optimized operating point; and (iii) Adaptive DSP-based noise cancellation to compensate for multiplicative phase noise resulting from platform vibration, Doppler shift, polarization rotation, fading and scintillation as detailed in previous publication[6].

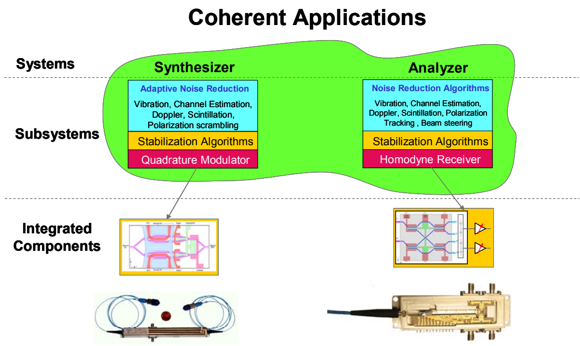

Figure 6. A unified layered architecture for fieldable digital coherent interferometric communications and sensing.

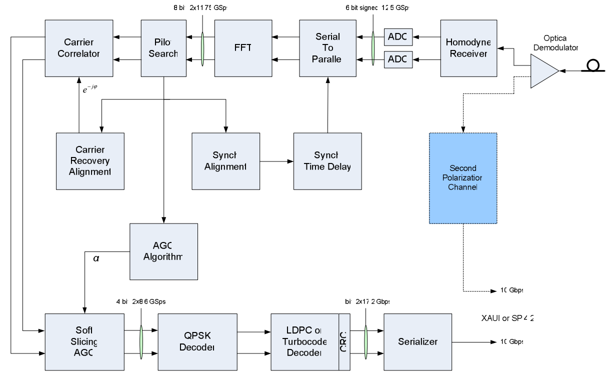

Figure 7. OFDM receiver DSP architecture.

In the case of free space optical communications the *Synthesizer* provides: Agile synthesis of key-based multi-dimensional hopping in time, frequency, polarization state, coherent modulation scheme (e.g. M-PSK, M-QAM) and symbol rate to adapt to an optimal combination of security against jamming and eavesdropping, spectral efficiency and atmospheric conditions in the tactical environment.

In the latter application the *Analyzer* embodies*:* Coherent detection of a generalized key-based multi-dimensionally hopped coherent optical signal via a generalized Homodyne Polarization Diversity Receiver with DSP-based adaptive algorithms that digitally extract the information content from both channel noise and key-based multi-dimensional optical scrambling without the use of optical frequency and polarization tracking and unwinding. High spectral efficiency fiber based coherent communications utilizing our components are described elsewhere[1,5].

By co-locating the synthesizer and analyzer and sharing a common optical local oscillator one can design interferometric sensing applications such as Coherent LADAR or Vibrometery using a common layered architecture with the unique ability to switch applications via software control.

The performance of the CLRR depends critically on the DSP algorithms to recover the laser radar return signal. Figure 7 shows a block diagram of the DSP architecture that process the OFDM signal. Details of the architecture will be presented.

SUMMARY

In this paper, we have presented the concept of novel digital receiver architecture for a CLRR based on temporal diversity of two orthogonal polarizations with optical OFDM signaling. The CLRR employs MMF for efficient coupling followed by AO and SMF and eventually into the ICR. The concept and core elements of the receiver as well as the critical DSP stacks have been introduced.

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