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Precision Fiber Optic Links for Transporting Signals Off Cryogenic Infrared Focal Planes

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ABSTRACT

The high performance Infrared Focal Plane Array (IRFPA) detectors used by surveillance sensors for data acquisition, discrimination and track and on hit-to-kill interceptors produce vast amounts of data of wide dynamic range (> 80 dB) and high bandwidth (> 10 MHz). Signal processing requires these data be digitized so that linearization, temporal and spatial filtering, coincidence rejection and discrimination algorithms may be applied. Fortunately, all of these functions can readily be performed with existing room temperature digital hardware, in the form of Analog-to-Digital converters and Digital Signal Processor (DSP) chips.

One difficulty in carrying out the signal processing lies in the fact that since the FPA produces picoamp or nanovolt signals, they are highly susceptible to the effects of Electro-Magnetic Interference (EMI) in their transmission from the FPA cold finger to the warm off-dewar signal processor. A solution to the problem of EMI contamination is to be found in placing the digital processors near the cold FPA focal plane. However, this method of signal processing introduces a sizable heat load to the cryogenic environment which makes it less attractive.

An alternate approach to the processing of the digital signal at the FPA is to transport the FPA signal via an optical link to a remote processor. Visidyne has designed and tested such a

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link. The link is based on converting the FPA voltage to a phase modulated optical signal by means of a passive optical waveguide. The conversion is made by modulating the optical path length of two guided optical waves through the Pockels effect, a process that is extremely linear and has a large frequency (> GHz bandwidth) response.

The converted signal, can then be transmitted by means of optical fiber to the environment outside the dewar. Because the signal is transmitted optically, it remains immune to degradation through EMI and therefore maintains its fidelity. Once the optical signal is outside the Dewar, the FPA voltage can be recovered and digitized by means of an interferometer and standard DSP electronics as a digital representation of the IRFPA signal.

Key Words

Fiber, Optical, Link, Precision, Infrared

BACKGROUND

The cryogenically cooled Infrared Focal Plane Arrays (IRFPA's) produce large bandwidth (Mpixels/sec), small (picowatt, nanovolt) signals. During their transmission from the dewar cold finger to the warm outside world for further processing they are highly susceptible to Electro Magnetic Interference (EMI). This susceptibility has impaired a number of critical missions [1]. A number of efforts to minimize the perils of EMI such as the Mosaic Array Data Compression and Processing (MADCAP)[2] scheme has been initiated. MADCAP proposes to address the issue of EMI by moving the processing electronics, Analog-to-Digital Converters (ADC's), Digital Signal Processing (DSP) chips to or near the FPA . The processed signals would then be transmitted as a high rate digital bit stream. This requires specialized chip designs and packaging techniques to operate at reduced temperatures, and in addition would increase the heatload on the dewar while potentially causing EMI of its own. An effort to overcome the low temperature limits of the electronics using superconducting elements for the electronics, has been sponsored by BMDO at JPL and TRW[3] . However, one potential problem appears to be a serious impedance mismatch between the FPA and the superconducting ADC.[4] A natural solution in light of the success of optical, analog and digital communication networks is to consider an optical method of transmission through the modulation of an optical carrier by the FPA signal. In fact, a number of attempts to design such a capability have been made. They have either been based on the direct current modulation of a laser diode intensity with the signals from the FPA[5] or indirect intensity modulation using an interferometric device in the form of a Mach-Zehnder (MZ) interferometer implemented as an a optical waveguide.[6] Both these approaches, while having sufficient bandwidth, fall short in terms of resolution and precision since both these modulation processes are inherently non-linear, affected by operating point stability and suffer from added noise due to relative laser intensity noise (RIN). A solution Visidyne has chosen is to modulate the phase of the optical carrier by varying the optical path difference between two optical beams through a strictly linear electro-optical process. Once the beams are outside the dewar, the FPA signals are recovered as a binary, weighted digital representations of the original signal.

Phase Modulated Optical Link

The overall concept for a precision phase modulated optical link is illustrated in Figure 1. The voltage from the IRFPA detector is applied, with or without additional amplification, gain G, to a balanced pair of optical waveguide modulators. These sustain a single polarization and spatial mode, and are commonly implemented on a $LiNbO_3$ crystal substrate. They are physically small, < 1" long, and a few mm wide. The applied voltage introduces a path difference of approximately 125 nanometers per volt, or for a wavelength of $\lambda = 800\ nm$, a signal voltage of approximately $3.4\ V$ will introduce a phase shift of ≈ 400 nm or $\lambda/2$, half a cycle, π radians, a value often called V_π. An optical fiber pair, driven in push-pull configuration, would require only a voltage of V_π for a full cycle of phase shift, 2π. One advantage of waveguide modulators lies in their low heat dissipation due to their very high impedance. In addition, the modulator response is strictly linear with applied voltage (see inset of Figure 1), over many cycles of phase, up to the breakdown voltage limit of at least 10 cycles. The modulator remains nearly instantaneous in their signal response for frequencies greater than 3 GHz

As outlined in Figure 1, the light from a small laser diode external to the dewar is brought in by a single mode fiber, and equally divided into the two arms of the waveguide modulator.

Two exit fibers then bring the two output beams having the differential phase shift $\phi = V\,G/V_\pi$ to an outside interferometer/receiver after which a digital phase processor recovers the phase shift as a digital representation $\Phi = \phi_{min}{}^{2(n-1)} + 2^{(m-1)}$, where the first term to the right of the equation, ϕ_{min} , represents the fractional phase and the second term the number of whole cycles. Typically the minimally resolvable phase value of $\phi_{min} = 10^{-4}$ cycles, is equivalent to a path difference resolution of approximately 80 pm for a bandwidth of > 10 MHz. The second term is usually limited to 1 to 2 cycles, for a total dynamic range of 2 x 10^4 (≈ 14 bits, or 86 dB). The key difference between this approach and those cited previously, is instead of carrying the signal information as in intensity modulation, the information is carried as a differential phase shift between two optical beams, carriers. The fundamental advantage of modulating the phase, is that the signal phase is independent of the received light level, power on the receiver, including those due to changes in laser output and fiber losses. This is because the phase is recovered as a ratio between two signals and is not affected by laser intensity noise making it possible to reach shot noise limited sensitivity down to very low frequency.

Precision High Resolution Phase Recovery

It is critical to the success of the design to recover the phase $\phi(t) = V\,G(t)/V_\pi$ between the two beams at some fundamental, shotnoise or detector noise limit at large bandwidth (>10 MHz) and with a high degree of precision, linearity, and DC stability. At Visidyne we use a phase diversity receiver that simultaneously produces, at least three signals, from the interferometer/receiver with a precisely controlled phase shift between them.

In the case of 120° phase offset (1/3 of a cycle) the sampled spatial fringe pattern produces three voltage signals:

$$I_R = I_{DC} + I_A(\cos 2\pi\phi(t) + 0) + I_N \qquad I_S = I_{DC} + I_A(\cos 2\pi\phi(t) + 1/3) + I_N$$

$$I_T = I_{DC} + I_A(\cos 2\pi\phi(t) + 2/3) + I_N$$

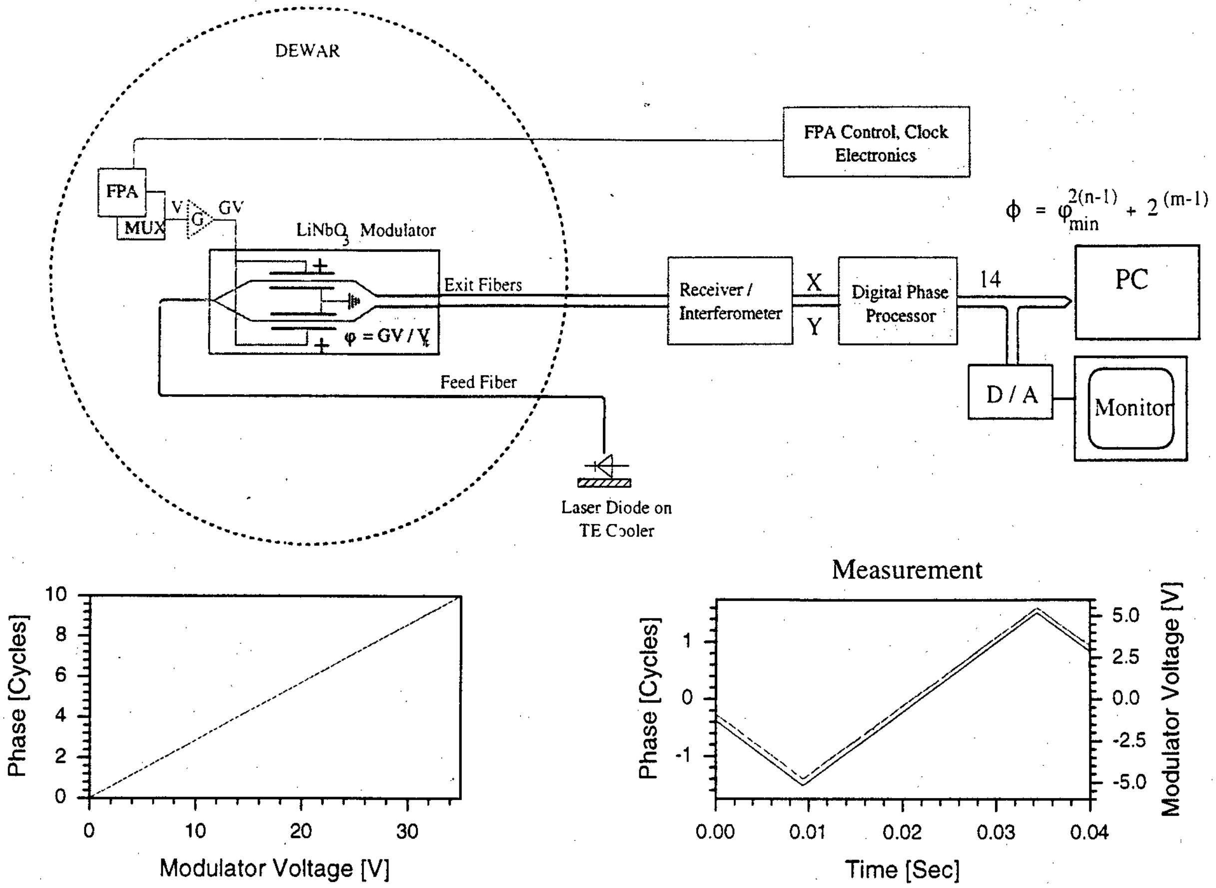

Figure 1 The Cryogenic Optical Link

where I_R, I_S, and I_T are three signals, I_{DC} is a common DC brightness level and I_{AC} a common AC amplitude, proportional to interference fringe visibility. One way to solve for the phase, $\phi(t)$, is to condense these three signals down to two quadrature signals, by the algebraic step of $X(t) = \sqrt{3}/2\ (I_S - I_T) = I \sin 2\pi\phi(t)$ and $Y(t) = I_R - 1/2\ (I_S + I_T \cos 2\pi\phi(t))$.

The two signals, $X(t)$ and $Y(t)$, after being digitized to e.g., 13 bits are applied to a high speed > 20 MHz coordinate transformation chip. The chip then computes the instantaneous phase up to a resolution of 13 bits using an arc tangent transformation and a high speed look-up table equivalent to $\phi(t) = \tan^{-1} X(t)/Y(t)$. Due to the ratiometric nature of this process the effect of any added laser intensity noise I_N is then cancelled and remains unaffected by temperature and operating point while having excellent resolution and bandwidth capability.

However the encoding of the signal as phase modulation introduces a problem which does not exist when the intensity modulation method is employed. Since the exit fibers are part of the interferometer, any path differences between the fibers e.g., due temperature, pressure, vibration manifest themselves as equivalent signals or phase errors. As the least significant bit may represent a phase shift of $1/2^{13}$ cycles or a path difference of $\lambda/2^{13} = 0.1$ nm, the two fibers should be kept to a relative difference to fractions of a nanometer. For the case e.g. of 3 meters of fiber length a relative, differential stability of $1/2^{13}$ which would appear to be a formidable challenge. In practice, as will be shown, the required degree of stability can be realized over the period of a video frame e.g. 10 to 30 msec.

A number of factors contribute to optical fiber length stability. First, the optical fibers are made of the highly homogeneous material, fused silica and therefore have very predictable effects with temperatures and pressure. When the two optical fibers are packaged in close proximity, a high degree of common mode rejection to environmental influences results. For example, while a single fiber's optical path length changes by 17 cycles/ m °C, two bundled fibers have a *differential* optical path difference is reduced to 0.5 cycles/meter °C.

Secondly, since any drift due is only important as it occurs over a period of a frame, drift rates per frame of $< 10^{-4}$ cycle are then readily attainable as temperature changes greater than 0.1 °C/sec are unlikely in a normal environment such as a satellite.

Sources of Error

There are a number of sources of error, random noise and systematic, which may affect the performance of the Cryolink optical readout. Random sources include detection/preamp, thermal and shot noise statistics as well as quantization errors of the phase processor. A number of noise sources associated with unintentional phase changes may also occur.

For example, systematic errors due to the thermo-mechanical strain in the exit fibers may create a path difference between the two optical fibers. Or the laser diode wavelength may drift due to a temperature/current change. Small errors associated with non-uniformities between pixel sensitivity, as well as mismatch between the pitch of the interferometer fringe pattern and the detector spacing array may occur. Additionally, computational errors in the phase processor will be present in the calculation of the phase. These errors can be collectively described as φ_{tot}, expressed in cycles or as an equivalent input noise voltage, $e_t = (\varphi_{tot}\ V_\pi\ )/G$,

$$\varphi_{tot} = \frac{1}{m_e}\left(\frac{2eB}{R_i P_d}\right)^{1/2} + \frac{1}{2^{(n-1)}} + \frac{ds}{dT}\frac{dT}{dt}\Delta l t_{frame}\sigma + \frac{d\sigma}{dt}\Delta l t_{frame} + \varepsilon_{\det} + \varepsilon_{proc}$$

The first term on the right is the detector shot noise component where $e = 1.6 \times 10^{-19}$ C, B the detector/preamp bandwidth (5 MHz), R_l the detector response (0.6 A/Watt) and P_d the detector power and m_e is the modulation efficiency of the interferometer. Due to the finite width of the detector elements, $m_e = 0.7$. For $P_d \geq 1$ *mW*, the detector shot noise dominates, $\varphi_{tot} = 5 \times 10^{-5}$ cycles.

The second term is associated with the quantification noise of the processor. For full scale e.g. ± 5 Volts signal, the phase resolution of the processor is $\geq 1/2^{13} = 10^{-4}$ *cycles.* The third term represents the influence a temperature drift on the differential optical path length of the paired fibers. Assuming a change in the thermo-mechanical strain, $ds/dT = 1.5\ 10^{-5}$ *[cycles/°C m]*, and fiber pair matched to a length, $\Delta l = 1$ *mm*, temperature drift rate of $dT/dt = 0.1$ *°C/sec,* a wavelength of $\sigma = 1/\lambda = 12{,}000\ cm^{-1}$, and IRFPA frame rate of e.g. 100 frames/sec, $t_{frame} = 10$ *msec,* $\Delta\varphi(t)$ will result in a total phase error of 1.8×10^{-7} cycles.

The fourth term represents the phase drift due to a wavelength change rate of $d\sigma/dt$. With even a minimal laser diode temperature control, phase drift is negligible. The last two terms, describing the detector and processor noise, ε_{det} and ε_{proc} each are will below $< 10^{-4}$ cycle.

Experimental Demonstration

A test image was recorded of the AFRL logo as shown in Figure 2. The image was created using first generation detectors and auxiliary electronics of limited bandwidth (100 kHz). The limited bandwidth of the detector/amplifiers results in a slightly blurred image. Slight drifts in the lines defining the borders of forms are to be seen and are caused by drift rates of roughly

Figure 2 An Example of a Cryolink Transmitted Image

10^{-4} cycles/sec. We expect that the planned improvements in bandwidth and in packaging of the optical fibers will allow for marked improvements of the picture clarity.

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