SECURE OPTICAL COMMUNICATIONS UTILIZING PSK MODULATION, POLARIZATION MULTIPLEXING AND COHERENT DIGITAL HOMODYNE DETECTION WITH WAVELENGTH AND POLARIZATION AGILITY

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ABSTRACT

Data Encryption and User Authentication are the major communications security (ComSec) approaches used in today's communications networks. While these methods provide an efficient means to secure the sensitive information, they do not prevent a hostile opponent from jamming the signal or tapping the link. We present here an analysis of a coherent optical communications system providing secure communications in free-space or over fiber.

After reviewing the basic principles of Coherent Optical Communications we present a system using polarization/frequency agility to secure the data link at the optical layer. The key building blocks will be presented, including a QPSK transmitter, and an optical hybrid combined with a coherent digital receiver. A description of CeLight's $LiNbO_3$ integrated implementation of the transmitter and the receiver will be detailed.

Next, a theoretical analysis demonstrating the capabilities of such a secure communications system to send data over fiber and in free space eliminating the need for optical filtering and lambda-based de-multiplexing.

Finally, we present an experiment demonstrating the ability of the proposed frequency hopping solution to avoid an eavesdropper from intercepting the data channel.

INTRODUCTION

Techniques used today to secure communications networks consist of Data Encryption and User Authentication. Data encryption makes the deciphering of information that has been accessed without authorization more difficult, while user authentication procedures are used to prevent unauthorized users from gaining access to the data in the first place.

While these methods provide ways to secure sensitive information, they do not prevent physically tapping into the link and collecting the transmitted data. Commercially available off the shelf equipment provides such optical link tapping capabilities, enabling the interception and collection of data. Increasing computation power and efficient algorithms may enable the eventual deciphering of this maliciously collected data.

We present here a method and system based on CeLight's VectorWAVE™ platform to provide a more fundamental level of security to the communications link at the optical layer, whether free-space or fiber, making the malicious collection of data considerably harder.

The proposed method includes using phase shift keying (PSK) modulation and coherent digital homodyne detection. This modulation and detection scheme provides inherent frequency selectivity and enables the incorporation of wavelength agility into the communications link without reliance on narrowband tunable optical filters. In addition, the preservation of the signal phase information in the receiver enables the implementation of a digital polarization diversity receiver without reliance on optical components, thus making polarization multiplexing and polarization agility implementable. As a result, a potential eavesdropper will have to use more complex receivers, covering a much wider bandwidth of optical spectrum and develop a novel class of devices accounting for the rapid signal polarization changes of the multiplexed signals.

SECURE OPTICAL LAYER COMMUNICATIONS SYSTEM

Figure 1 shows a single transmitter, one of many to be used in such a secure optical Communications system. A low linewidth tunable laser is optionally intensity modulated using a Mach-Zehnder Interferometer (MZI) and shaped into a train of RZ (return to zero) pulses. The carrier is split into two paths; each intended to carry data on a different polarization state (H and V). The data is encoded in the phase of each of the optical carrier polarization component using a phase modulator or a quadrature modulator, e.g. CeLight's $LiNbO_3$ quadrature modulator shown in Figure 2. The two signals are then added on two orthogonal polarization states using a polarization beam combiner (PBC) and transmitted. A polarization scrambler may be used to change the polarization state of the signal.

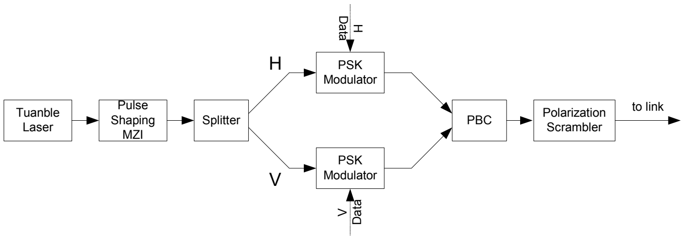


Figure 1. PSK dual-polarization transmitter schematic. A low linewidth tunable laser is shaped into a pulse train using a MZI, then split into two paths each modulated with an independent data stream using a PSK modulator, and combined again on orthogonal polarization using a polarization beam combiner (PBC). A polarization scrambler is used to rapidly change the polarization of the transmitted signal enhancing its immunity to tapping.

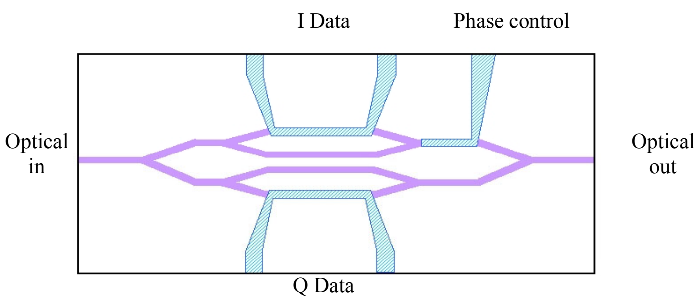


Figure 2. CeLight's $LiNbO_3$ QPSK modulator schematic. The carrier signal is divided into two arms, carrying the in-phase (I) and quadrature-phase (Q) parts of the modulation. A MZI on each arm modulates the carrier's amplitude according to the data, and a 90° phase shift is induced between the two arms using a phase modulator (PM). Finally, the two arms are combined using a coupler.

In the receiver, schematically shown in Figure 3, the signal is split into two (arbitrary) orthogonal polarizations (H' and V') and each is mixed with a local oscillator in an optical 90° hybrid. The hybrid, shown in Figure 4, takes the signal S and the local oscillator L and produces four outputs: (i) S+L, (ii) S-L, (iii) S+jL and (iv) S-jL. Each of the optical output pairs (i), (ii) and (iii), (iv) is collected by a pair of balanced diodes whose photocurrents are subtracted, as shown in Figure 5, to produce currents proportional to $|S+L|^2-|S-L|^2=4\cdot\mathrm{Re}\{SL^*\}$ and $|S+jL|^2-|S-jL|^2=4\cdot\mathrm{Im}\{SL^*\}$, together constructing the complex value SL^*. Following this (linear) transformation the signals are electrically filtered, sampled and then processed.

The local oscillator (laser) L, which is also tunable, is supposed to be phase-locked to the incoming signal S. The actual implementation of the phase-lock loop (PLL) is done in the digital part of the receiver, eliminating the need for a complex optical PLL. The optical hybrid and balanced diodes act as a mixer, down-converting the signal from the optical band to the electrical baseband. It is important to note that since the transformation is linear, all of the filtering (for noise reduction and separation of carriers) can be performed in the electrical domain, with no reliance on narrow optical filters. For the same reason the signal received by the DSP on arbitrary polarizations $[S_{H'}\ S_{V'}]^T$ can be rotated (by multiplying it with the appropriate recovery matrix, M) to recover the original polarization state of the signal $M\cdot[S_{H'}\ S_{V'}]^T=[S_H\ S_V]^T$, and the data on each polarization can then be demodulated.

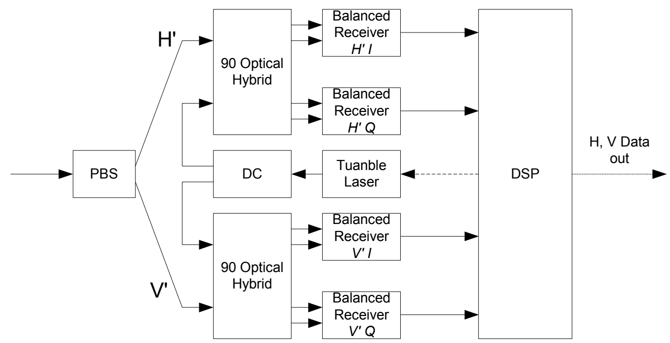
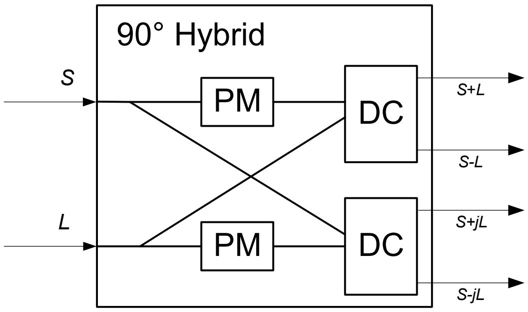
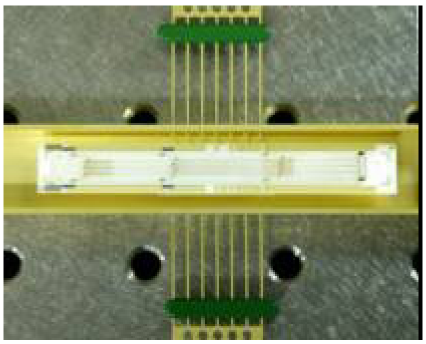


Figure 3. PSK dual-polarization digital homodyne receiver schematic. The incoming signal is arbitrarily split into two orthogonal polarizations using a polarization beam splitter (PBS), each polarization is input into a 90° optical hybrid, which mixes the signal S with a local oscillator L, shared by the two hybrids using a directional coupler (DC). Each hybrid output pair {(S+L), (S-L)} and {(S+jL), (S-jL)} is input into a balanced receiver that yields a signal proportional to Re{SL*} and Im{SL*} respectively. The digitized samples are processed to recover the original polarization state of the signal to compensate for the phase and frequency offsets of the lasers, and to demodulate the data.

The system presented above consists of many such transmitters and receivers sharing the same bandwidth, all changing wavelengths and polarization states synchronously or asynchronously (where the number of wavelength slots is much bigger than the number of carriers). Notice, that while it can be relatively easy to follow a carrier when there are no other carriers present, the presence of a significant number of carriers changing wavelengths synchronously or asynchronously makes the task harder.



(a)



(b)

Figure 4. 90° optical hybrid. The hybrid takes two input signals S and L, and mixes them with four relative phase relations, adjusted by the phase modulators (PMs): (i) S+L, (ii) S-L, (iii) S+jL, and (iv) S-jL. DC = Directional Coupler. (a) a schematic representation (b) CeLight's actual device.

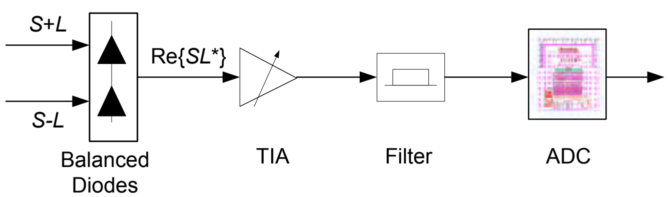


Figure 5. A balanced receiver schematic. A pair of balanced diodes detects the two light signals; their output is subtracted and amplified by a trans-impedance amplifier (TIA), filtered and sampled in an analog to digital converter (ADC).

ADVANTAGES OF THE SECURE OPTICAL COMMUNICATIONS SYSTEM

WAVELENGTH AGILITY

The main characteristic enabling the secure optical system discussed above is its wavelength agility. Each carrier can change its wavelength by tuning the lasers in the transmitter (serving as the signal carrier) and receiver (serving as the local oscillator). Some additional time (in the order of microseconds) will be needed to relock the receiver onto the incoming data stream. A major advantage of using such coherent detection scheme is that there is no need for narrow tunable optical components, whose tuning and settling times are on the order of several milliseconds, because the local oscillator transfers the optical signal linearly to the electrical domain.

POLARIZATION AGILITY

Another major advantage of the secure optical system discussed above is that no optical components are required in order to recover the polarization state of the signal in the receiver. The linear transformation of the signal from the optical to the electrical domain and its digitization enables the performance of digital polarization compensation, thus avoiding the problematic use of slow, non-endless optical polarization compensators, and the incurring losses [1]. Furthermore, an enhancement in the security level can be achieved by applying rapid changes to the polarization state of the signal using a scrambler in the transmitter, followed by the appropriate counter adjustment of the digital polarization compensation matrix in the receiver. Moreover, allowing the transmission of two different data streams on the same carrier frequency, using the two orthogonal polarization states, considerably increases the security level of the transmitted data, while doubling the channel capacity and spectral efficiency.

PERFORMANCE VS. CHANNEL NOISE

The secure optical system discussed above utilizes coherent phase shift keying (PSK) demodulation, in particular the preferred modulation scheme will be QPSK (quadrature PSK), where each symbol is encoded with two (2) bits per polarization, as shown schematically in Figure 6, [2]. It should be noted that CeLight's quadrature modulator 3], designed for QPSK modulation, is able to perform any modulation scheme (mPSK, QAM, etc.) given the appropriate driving electronics.

Figure 7 shows calculated BER vs. SNR per bit curves for QPSK/BPSK, DQPSK, DBPSK [3] and intensity modulation direct detection (IMDD) [5]. The noise is considered to be additive white gaussian noise (AWGN) and is added before the receiver (optical hybrid).

It is clear from these results that using QPSK modulation, the system can tolerate more than twice the noise compared to using IMDD. Note that the QPSK modulation scheme has double the spectral efficiency of BPSK.

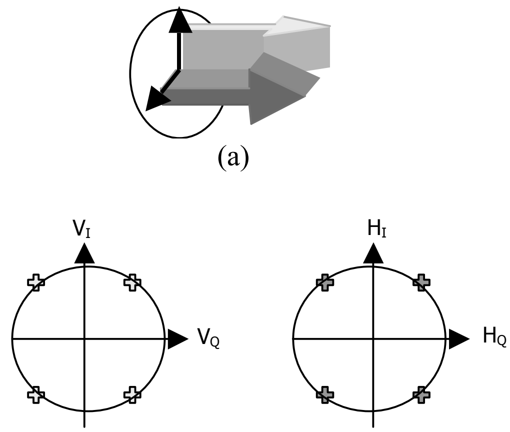


Figure 6. Polarization multiplexed QPSK signal constellation. The signal is divided into two orthogonal polarization states (a). On each polarization two bits are encoded, one on the in-phase (I) and one on the quadrature-phase (Q) of the signal (b).

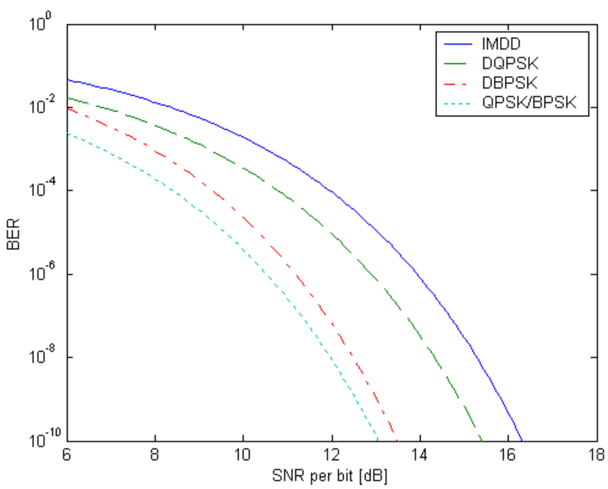


Figure 7. Calculated BER vs. SNR per bit for IMDD, DQPSK, DBPSK and QPSK/BPSK modulation schemes.

SPECTRAL EFFICIENCY

Using QPSK and polarization multiplexing enables transmitting four (4) bits of information per symbol (pulse). Accordingly, for the same signal bandwidth the secure optical communications system can deliver four times the information compared to an OOK or BPSK signal transmitted on a single polarization.

In addition, since no optical filters are used to separate carriers in the receiver, we can pack the channels more closely, relying on electrical filters to perform the separation. Accordingly, a spectral efficiency of 1.6 bits/sec/Hz (40Gbps over 25GHz channel spacing) can be readily demonstrated with these methods and devices.

PERFORMANCE VS. CHANNEL DISTORTION

Since the signal is down-converted linearly to the electrical baseband and digitized, the entire arsenal of digital signal processing methods conventionally used in RF systems becomes available for implementation in the system. Particularly, implementation of channel equalization and compensation for linear channel distortions (e.g. chromatic dispersion, PMD, some atmospheric effects etc.) is attractive.

ANALYSIS OF QPSK TRANSMISSION WITHOUT OPTICAL FILTERS

Assume that the incoming signal S is composed of N carriers, each with power P_s. The k^{th} carrier's angular frequency is ω_k, and its phase data is φ_k. An AWGN noise n_{amp} is added to the signal.

$$S = \sqrt{P_s}\sum_k e^{j(\omega_k t + \varphi_k)} + n_{amp} \qquad (1)$$

The local laser oscillator whose power is P_l is tuned to receive the k^{th} carrier

$$L = \sqrt{P_l}e^{j\omega_k t} \qquad (2)$$

The current in the I channel after the TIA without filtering is:

$$i = |S+L|^2\xi(1+\varepsilon) - |S-L|^2\xi(1-\varepsilon) + n_{shot} + n_{thermal} \qquad (3)$$

Here ξ is the average responsivity of the two balanced diodes, ε^2 is the common mode rejection ratio (CMRR), n_{shot} is the total shot noise (induced by the two balanced diodes) and $n_{thermal}$ is the thermal noise induced by the TIA.

After low pass filtering we have

$$\begin{aligned} i = 4\xi\left(\sqrt{P_s P_l}\cos\varphi_k + \sqrt{P_l}\,\Re\{n_{amp}^k\}\right) + \\ +2\xi\varepsilon\left(NP_s + P_l + 2\sqrt{P_s}\sum_l \Re\{n_{amp}^l\} + n_{amp}^2\right) + \\ +n'_{shot} + n'_{thermal} \end{aligned} \qquad (4)$$

With n^k_{amp} being the noise filtered with the receiver local laser oscillator tuned to ω_k, and n^2_{amp}, n'_{shot} and $n'_{thermal}$ are the filtered $|n_{amp}|^2$, n_{shot} and $n_{thermal}$.

Equation (4) consists of the following terms: the desired signal $4\xi\sqrt{P_s P_l}\cos\varphi_k$, the l-n beating noise $4\xi\sqrt{P_l}\Re\{n^k_{amp}\}$, the s-s beating interference that is (almost) constant with amplitude $2\xi\varepsilon(NP_s+P_l)$, the s-n beating noise $4\xi\varepsilon\sqrt{P_s}\sum_l \Re\{n^l_{amp}\}$, the n-n interference $2\xi\varepsilon n^2_{amp}$, the shot noise, and the thermal noise.

Assuming that (NSR_{s-n}, NSR_{n-n})<<NSR_{l-n} the total noise will be minimal when $NP_s=P_l=\frac{1}{2}P_{max}$, where P_{max} is the maximal power allowed on each diode. The above inequalities are true if $\varepsilon^2 \ll 1$, and $\frac{\varepsilon^2}{8N}\frac{BW_o}{BW_e} \ll 1$, where BW_e and BW_o are the receiver electrical and optical bandwidths, respectively. Also, NSR_{s-s} may be quite big (around 1), and must be lowered through common DC removal techniques.

LINK MEDIUM ANALYSIS

FIBER

In optical communications fiber links the amplifier noise comes mainly from the link in-line amplifiers. The level of the incoming signal can be controlled by a preamplifier, with a noise contribution that is assumed to be negligible compared to the noise already coming from the link.

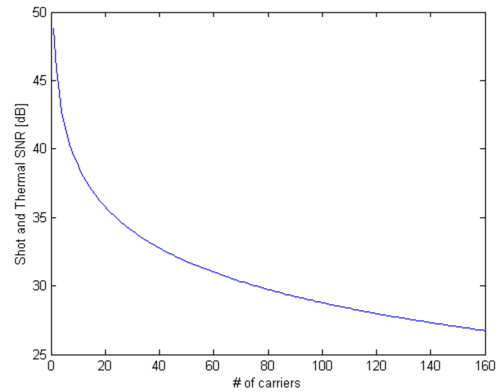
The total noise to signal ratio NSR, neglecting NSR_{s-n} and NSR_{n-n} and removing NSR_{s-s}, is

$$\begin{aligned} NSR &= NSR_{shot} + NSR_{thermal} + NSR_{l-n} = \\ &= N\left(\frac{2q}{P_{max}\xi} + \frac{SD_{th}}{(P_{max}\xi)^2}\right)BW_e + NSR_{l-n} \end{aligned} \tag{5}$$

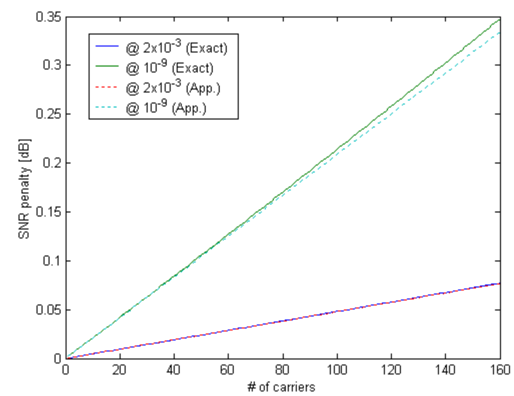
Where SD_{th} is the spectral density of the thermal noise and q the electron charge. The SNR penalty (in dB) is

$$\begin{aligned} SNR_{penalty} &= 10\log_{10}\left(\frac{NSR}{NSR - NSR_{shot} - NSR_{thermal}}\right) = \\ &\cong \frac{10}{\ln 10}\left(\frac{2q}{P_{max}\xi} + \frac{SD_{th}}{(P_{max}\xi)^2}\right)BW_e \cdot SNR \cdot N \end{aligned} \tag{6}$$

Figure 8 (a) shows the thermal and shot SNR as a function of the number of carriers in the optical filter passband with ξ=0.75A/W, BW_e=10GHz, $SD_{th}=(50\cdot10^{-12})^2 A^2/Hz$, and P_{max}=3dBm. Figure 8 (b) shows the SNR penalty vs. the number of carriers in the optical filter passband for a BER of 2×10^{-3} (9.2dB SNR) and 10^{-9} (15.6dB SNR).



(a)



(b)

Figure 8. (a) Combined Shot and Thermal noise SNR vs. no of carriers in optical filter; (b) Combined Shot and Thermal noise SNR penalty vs. no of carriers in optical filter at a BER of 2×10^{-3} (9.2dB SNR) and 10^{-9} (15.6dB SNR).

The results show that even when **160 channels** (!) are present in the optical filter passband, the penalty in the receiver will be small. Accordingly, the secure optical system discussed above can indeed enable the direct electronic filtering of a heavily populated C-band with hundreds of channels hopping simultaneously, delivering a capacity of 6.4 Tb/s.

FREE-SPACE

With P_{in} the power at the input of the receiver (preamplifier), we have $P_s = \frac{P_{in}G}{L} = \frac{P_{max}}{2N}$, and (for the I channel),

$$NSR_{1-n} = \left(\frac{h\nu NF}{P_{in}} - 2N\frac{h\nu NF}{P_{max}L}\right)BW_e \quad (7)$$

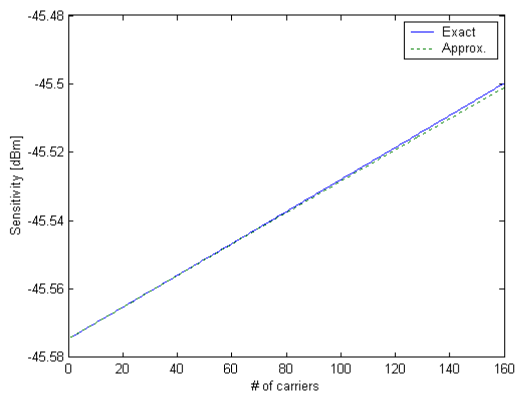
where NF is the preamplifier noise figure, L is the loss from the receiver input to the diode and hν the carrier photon energy. Ignoring the s-s, s-n and n-n noises we get

$$\begin{aligned} NSR &= NSR_{shot} + NSR_{thermal} + NSR_{1-n} = \\ &= \left[N\left(\frac{2q}{P_{max}\xi} + \frac{SD_{th}}{(P_{max}\xi)^2} - 2\frac{h\nu NF}{P_{max}L}\right) + \frac{h\nu NF}{P_{in}}\right]BW_e \end{aligned} \quad (8)$$

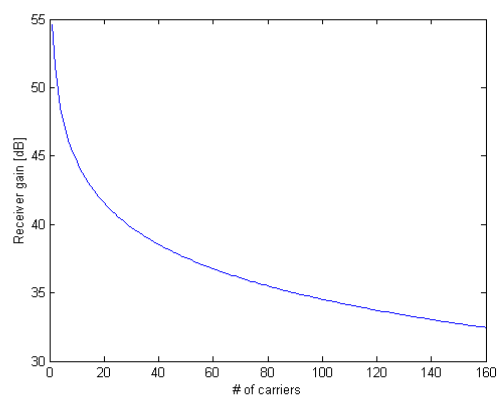
Solving for P_{in}

$$\begin{aligned} P_{in} &\cong h\nu \cdot NF \cdot BW_e \cdot SNR \cdot \\ &\cdot \left(1 + N\left(\frac{2q}{P_{max}\xi} + \frac{SD_{th}}{(P_{max}\xi)^2} - 2\frac{h\nu \cdot NF}{P_{max}L}\right)BW_e \cdot SNR\right) \end{aligned} \quad (9)$$

With $N\left(\frac{2q}{P_{max}\xi} + \frac{SD_{th}}{(P_{max}\xi)^2} - 2\frac{h\nu NF}{P_{max}L}\right)BW_e \cdot SNR << 1$.



(a)



(b)

Figure 9. (a) Sensitivity vs. number of carriers in the optical filter passband at a BER of $2x10^{-3}$; (b) Receiver preamplifier gain vs. number of carriers in the optical filter passband.

Figure 9 (a) shows the sensitivity as a function of the number of carriers at a BER of $2x10^{-3}$ with the parameters used previously before. Figure 9 (b) shows the receiver preamplifier gain $G = \frac{P_{max}L}{2NP_{in}}$ for the same conditions.

The results show that the sensitivity is hardly affected, even when **160 channels** (!) are present in the optical filter passband.

CELIGHT TRANSEC DEMONSTRATION

Following the above discussion we have performed a test to demonstrate the TranSec capabilities of the CeLight solution and the provision to integrate the ComSec and TranSec features into a total data security package. Specifically the purpose of this experiment was to demonstrate CeLight's wavelength hopping feature that prevents an eavesdropping receiver, employing either self-homodyne or homodyne detection from decoding the transmitted data.

The test setup is depicted in Figure 10. The Tx transmitter consists of a tunable laser source (TLS), a return-to-zero (RZ) pulse modulator and a data modulator that produce a binary phase-shift-keyed (BPSK) optical signal at 12.5 Gb/s. The wavelength of the TLS is periodically hopped to designated wavelengths based on input from the hopping controller. Note that the Tx ComSec unit was not available for this experiment. A commercial pattern generator was used to create an unframed pseudo-random bit sequence (PRBS) data to simulate the Tx ComSec unit's functions. The word length of the PRBS pattern used was 2^{15}-1. Two continuous-wave (CW) lasers (λ_1 and λ_3) were combined with the TLS to simulate DWDM channels in optical networks. All three lasers were modulated with the same PRBS data. The TLS wavelength was tuned to 1545.32 nm while λ_1 and λ_3 are tuned to ±25 GHz from 1545.32 nm. The BPSK signal was transmitted through approximately 1 km of single-mode optical fiber. The transmitted BPSK signal and a local laser oscillator (LO) are directed to the CeLight's coherent Rx.

The LO is derived from the TLS to ensure phase and frequency locking. The BPSK signal and the LO counter-propagated through the same 1-km of fiber using optical circulators to maintain phase coherency and reduce phase drifts. The transmitted BPSK signals and LO were amplified and directed to the CeLight's Lithium Niobate (LN) 90° optical hybrid. Polarization states of the input signal and LO were adjusted to align to the axis of the hybrid using manual polarization controllers. Two of the outputs of the hybrid were connected to a balanced detector. The balanced detector electrical output was connected to either a sampling oscilloscope or an error detector for eye pattern display or BER measurement. In order to obtain maximum eye opening a phase control loop was constructed to stabilize and maintain the proper optical phase shift between the BPSK signal and the LO. The output of the hybrid was tapped and detected to produce a feedback signal proportional to the opening of the eye pattern. The feedback signal was processed by a desktop computer, which produces phase control signals connected to the phase shifter and the optical hybrid as shown in Figure 10. Only two phase control signals were used. Due to the limited output voltage range of the phase control signal, reset of the loop occurred from periods of 30 seconds to 10 minutes depending on factors such as the control loop parameters, phase and polarization drifts as a result of environmental perturbations. Note that a clock recovery at the receiver was not employed in the test. The clock output from the pulse pattern generator was connected to the error detector for synchronization.

The self-homodyne and homodyne eavesdropper setups are shown in Figure 11. The self-homodyne eavesdropper used an asymmetric Mach-Zehnder (AMZ) interferometer to demodulate the BPSK signal. The AMZ interferometer was an optical delay-and-add device with a differential delay corresponds to one symbol period (80 ps). The homodyne eavesdropper combined a LO with the tapped BPSK signal using a fiber 3-dB coupler. The LO was a CW laser at 1546.37 nm. The outputs for the two eavesdroppers are displayed on a sampling oscilloscope.

Figure 12 shows a typical eye diagram of the 12.5 Gb/s RZ-BPSK at the CeLight's Rx balanced detector output for one transmitted channel (λ_1 and λ_3 turned off). The measured BER for this case is better than 10^{-9}. Note that a momentarily closing of the eye occurs during wavelength hopping of the BPSK signal. This is due to the settling time of the TLS and the phase control loop. The wavelength hopping of the BPSK signal was monitored with an optical spectrum analyzer (OSA) and a wavelength meter.

Figure 13 and Figure 14 show the oscilloscope display of the self-homodyne eavesdropper output for one and three transmitted BPSK signals, respectively. No stable eye pattern can be obtained at the eavesdropper's Rx as the wavelength of the BPSK signal hops. This is the case if the eavesdropper fails to keep track of the AMZ's differential phase shift (0 or π for BPSK) with the signal wavelength. For the multi-channel case (Figure 15), the eavesdropper will need a tunable optical filter to reject other channels and the optical filter must keep track of the hopping signal wavelength in order to recover the transmitted data.

Figure 15 shows the oscilloscope display of the homodyne eavesdropper output when the wavelength of one BPSK signal (1545.32 nm) is far from that of the eavesdropper LO (1546.37 nm). No eye pattern can be observed for this case.

Figure 16 shows the oscilloscope display of the homodyne eavesdropper output when the wavelength of one BPSK signal is approximately equal to that of the eavesdropper LO. An eye pattern can be seen, however, the eye is closed since phase-locked loop was not implemented.

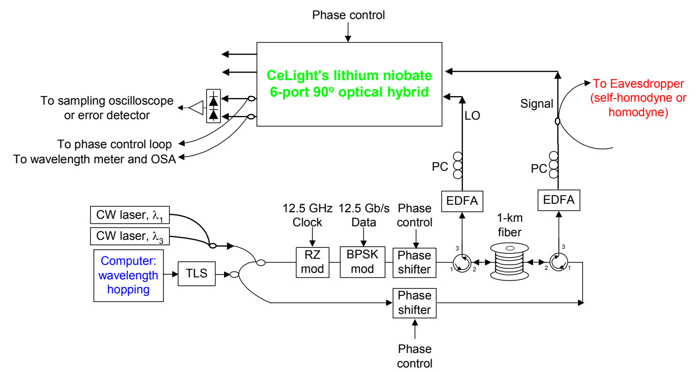


Figure 10. Setup with self-homodyne or homodyne eavesdroppers.

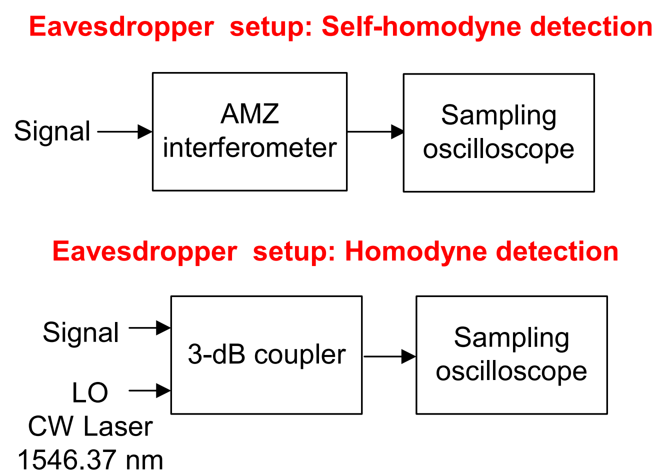


Figure 11. Eavesdroppers setup. Top: Self-homodyne detection with asymmetric Mach-Zehnder interferometer. Bottom: Homodyne detection with fixed wavelength CW local laser.

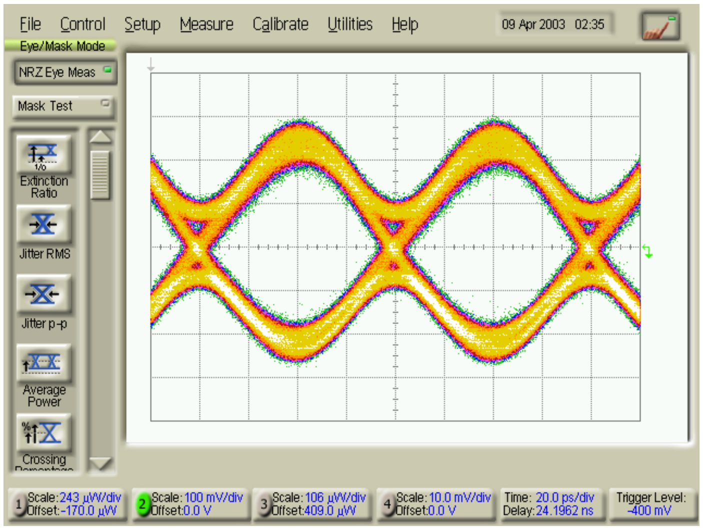


Figure 12. Homodyne detection of 12.5 Gb/s RZ-BPSK signal. One channel transmitted.

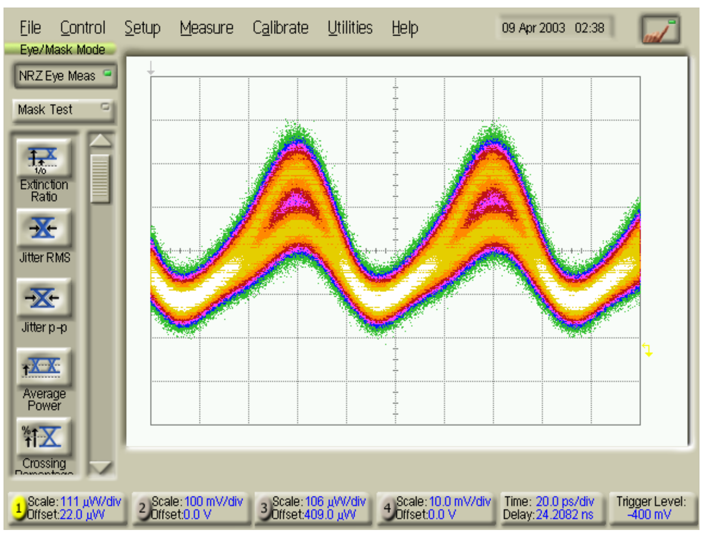


Figure 13. Eavesdropping with self-homodyne detection. One channel transmitted. No stable eye pattern.

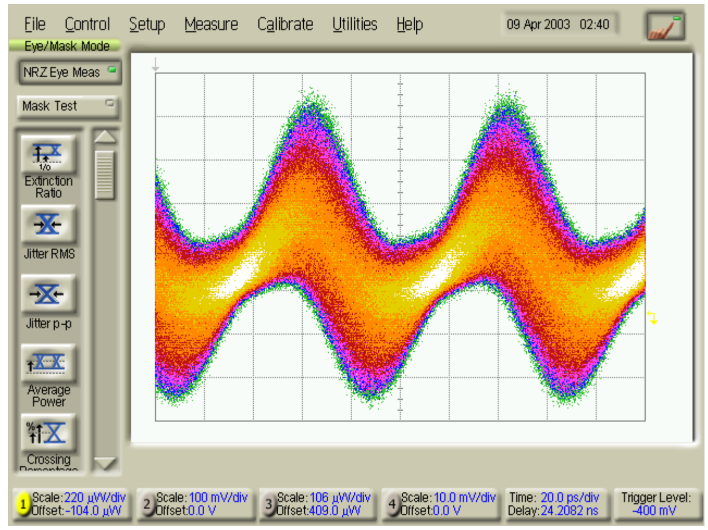


Figure 14. Eavesdropping with self-homodyne detection. Three channels transmitted. No stable eye pattern.

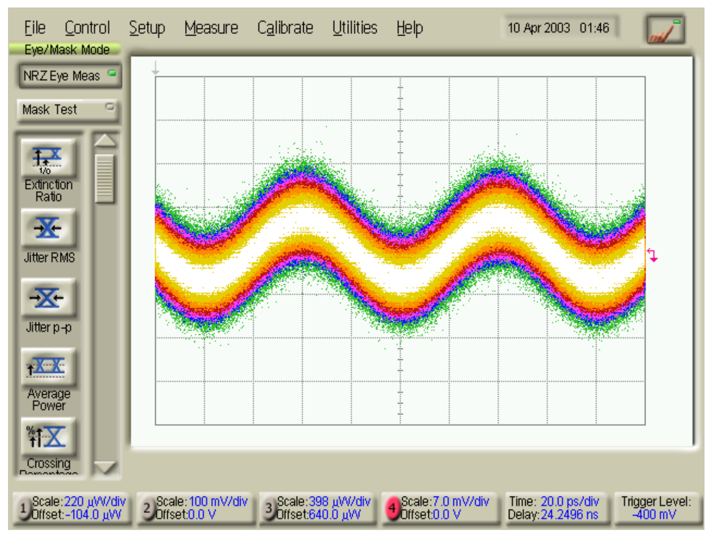


Figure 15. Eavesdropping with homodyne detection. Local laser wavelength: 1546.37 nm. Signal laser wavelength: 1545.32 nm. No eye pattern.

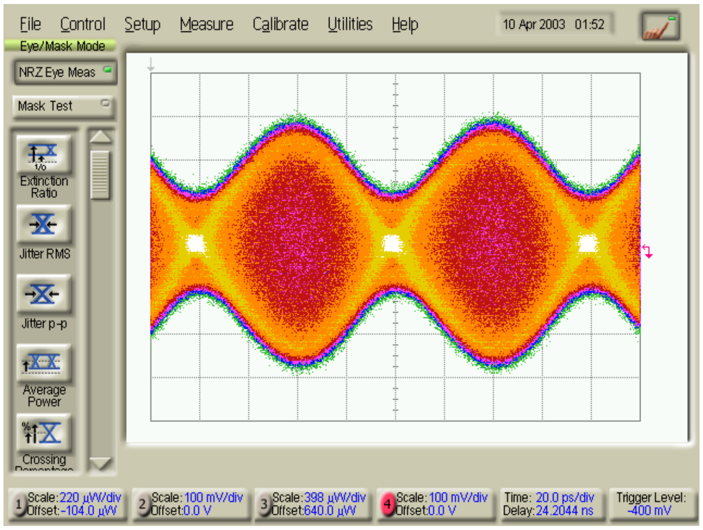


Figure 16. Eavesdropping with homodyne detection. Local laser wavelength approximately the same as the signal wavelength.

SUMMARY

In summary, we have presented and analyzed an optical secure communications system in free-space or over fiber. We presented the system architecture, based on CeLight's VectorWAVE™ platform using wavelength/polarization agility to secure the optical layer. The key building blocks were presented, including a QPSK transmitter, an optical hybrid and a digital homodyne receiver.

We have reviewed the basic principles of Coherent Optical Communications and compared various demodulation methods to conclude that the system presented above is poised to display superior performance.

Next, we presented a theoretical analysis showing that either in fiber links or in free space ones the secure optical system discussed above eliminates the need for any optical filtering. Thus, allowing a considerable cost reduction as well as extreme rapid hopping.

Finally, we performed an experiment demonstrating the ability of the proposed frequency hopping solution to avoid an eavesdropper from intercepting the data channel. The eavesdropper in this experiment was simulated for using either a self-homodyne or a homodyne receiver. In both cases it was demonstrated that it couldn't decode the data transmitted over the frequency hopping secure channel.

The above discussion and demonstration present an indication to the potential of utilizing such a solution to considerably enhance communications security at the physical layer. Further investigation and development is still required in order to deliver a full solution that utilizes this technology for various defense and commercial applications.

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