

# QPSK Transmission over Free-Space Link at 3.8 $\mu\text{m}$ using Coherent Detection with Wavelength Conversion

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## Abstract

We demonstrate the first mid-infrared free-space optical link employing coherent detection and parametric wavelength conversion.

## Introduction

Optical components for transmission near 1.55  $\mu\text{m}$  are a mature technology. Tunable lasers, modulators and balanced receivers at this wavelength are widely available. Numerous experiments have demonstrated the feasibility of coherent detection at 1.55  $\mu\text{m}$  in single-mode fiber. In free-space transmission, atmospheric absorption, Mie scattering and Rayleigh scattering are the dominant channel impairments. It has been shown that the mid-infrared (MIR) range offers low-loss transmission bands, and the effects of scattering and scintillation are less severe at longer wavelengths [1]. To take advantage of optical components that are available at 1.55  $\mu\text{m}$ , and the superior link performance at 3.8  $\mu\text{m}$ , we propose a hybrid system where the transmitter and receiver operate at a wavelength near 1.55  $\mu\text{m}$ , and suitably designed wavelength converters are used to down- and up-convert between the two bands. This enables a flexible system architecture where transceivers developed for optical fiber can be used for free-space communications at any wavelength.

## Experimental Setup

Our experimental setup is shown in Fig. 1. At the transmitter, a 1.55- $\mu\text{m}$  continuous-wave (CW) tunable laser is modulated by a quadriphase-shift-keying (QPSK) modulator to produce a 2.488-Gbit/s NRZ-QPSK output, which is followed by two erbium-doped fiber amplifiers (EDFAs) to boost the transmitted power to the correct level, before conversion to 3.8  $\mu\text{m}$  using an optical parametric wavelength converter. The MIR signal is propagated through a free-space link consisting of 1.5 m of air and two gold mirrors. At the receiver, the 3.8- $\mu\text{m}$  signal is coupled into a second wavelength converter that shifts the signal back to 1.55- $\mu\text{m}$ . Coherent detection follows.

The linewidths of the transmitter (TX) and local oscillator (LO) lasers in this experiment are 8 kHz and 15 kHz, respectively. The coherent receiver

employs heterodyne downconversion, where the difference between the optical frequencies of the TX and LO lasers is the intermediate frequency, which is 4.5 GHz for this experiment. Carrier synchronization is achieved using an analog fourth-order, second-order, electrical phase-locked loop (PLL) with optimized parameters [2].

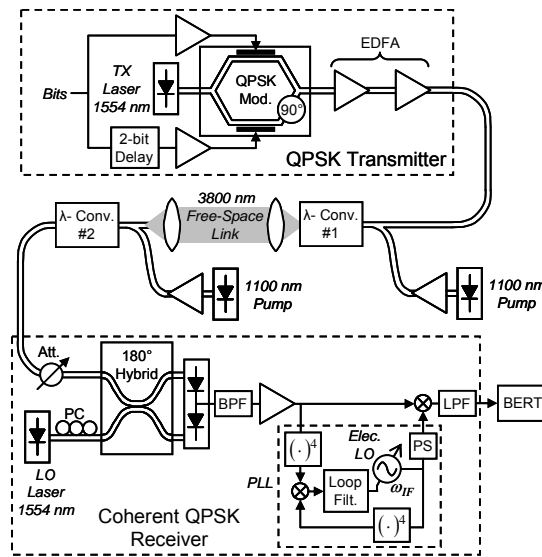


Figure 1: Experimental setup

For the wavelength converters, we used periodically poled z-cut lithium niobate crystals with Ti-indiffused waveguides (Ti:PPLN). Conversion between 1.55  $\mu\text{m}$  and 3.8  $\mu\text{m}$  is achieved through difference frequency generation (DFG), using a 1.1- $\mu\text{m}$  pump source. At the transmitter side, the pump and signal powers are 150 mW and 80 mW, respectively. The power of the 3.8- $\mu\text{m}$  output was measured behind a germanium filter to be 5 mW. At the receiver side, the same pump power produced 0.1 mW of radiation at 1.55  $\mu\text{m}$ , measured at the fiber input to the coherent receiver. Thus, the wavelength conversion processes and free-space propagation yielded a fiber-to-fiber loss of 29 dB.

## Results

We measured the bit-error ratio (BER) versus received power at 1.55  $\mu\text{m}$  by varying the attenuation before the 180° hybrid. Our results are shown in Fig. 2. The solid line shows ideal performance. The 'x' represent back-to-back performance of the 1.55- $\mu\text{m}$  coherent receiver without wavelength conversion or free-space transmission. The ' $\Delta$ ' represent the performance obtained with the setup of Fig 1. At BER =  $10^{-8}$ , the required 1.55- $\mu\text{m}$  signal levels are 12, 26 and 27.5 dB photons/bit, respectively. Comparing experimental data without and with wavelength conversion, we observe a power penalty of about 1.5 dB. This is caused mainly by amplified spontaneous emission (ASE) of the EDFAs at the transmitter. In Fig. 3, we show an eye diagram measured at the coherent receiver output, at a received 1.55- $\mu\text{m}$  signal level of 30 dB photons/bit, with wavelength conversion and free-space propagation.

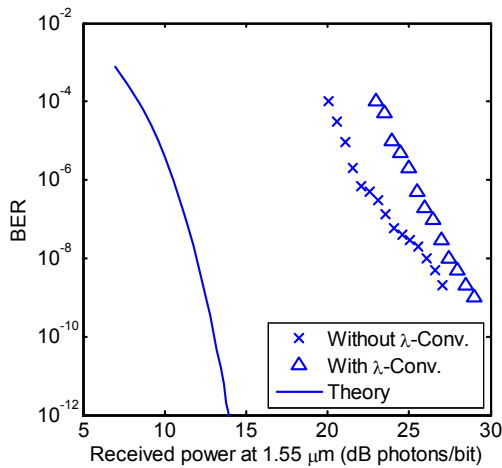


Figure 2: BER performance of coherent free-space link with wavelength conversion

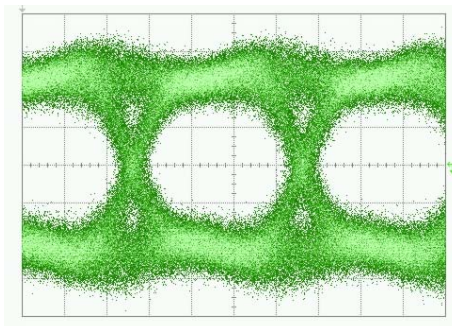


Figure 3: Electrical eye diagram

## Discussion

The noise sources in our system include ASE noise of the EDFAs at the transmitter; amplified parametric noise of the wavelength converters; and

shot noise and thermal noise of the receiver. Of these noises, receiver shot noise and thermal noise are dominant, due to the high coupling loss from the wavelength converter to the 1.55- $\mu\text{m}$  receiver. When measured in terms of the 3.8- $\mu\text{m}$  signal level at the input of the receiver wavelength converter, the sensitivity at BER =  $10^{-8}$  is 50 dB photons/bit, which is limited mainly by coupling losses and conversion efficiency.

The losses of the wavelength converters can be attributed to several sources. We found that in each converter module, the losses in fiber-optic components accounted for 2 dB of loss, while 3.6 dB of loss occurs at the waveguide boundary due to Fresnel, coupling and material losses. In the free-space path, the mirrors and lenses account for more than 1 dB attenuation of the 3.8- $\mu\text{m}$  signal. When coupling from free space to the receiver wavelength converter, 7.6 dB of loss occurs due to inexact collimation and mode coupling, polarization instabilities, and inexact phase-matching caused by temperature fluctuations. We calculated the photon conversion efficiencies of the DFG wavelength converters to be 25% for the transmitter and 12% for the receiver. Some of the losses reported above may be reduced with optimized design.

The performance of an ideal coherent receiver is limited by shot noise. In our experiment, thermal noise is non-negligible due to insufficient LO power, which is limited to avoid optical damage to the balanced photoreceiver. This resulted in a 5-dB power penalty. A further 3-dB power penalty is attributed to an excess bandwidth (2 GHz) of the electrical lowpass filter (LPF) after the demodulator. Phase noise, RF reflections, and the non-ideal passband characteristics of the electrical components resulted in a further 2-dB power penalty, yielding a 10-dB gap between the back-to-back performance (without wavelength conversion) and the ideal theoretical limit.

## Conclusions

We have transmitted a 2.488-Gbit/s QPSK signal over a free-space optical link at 3.8- $\mu\text{m}$  wavelength, and have detected the signal coherently. We used 1.55- $\mu\text{m}$  transmitter and receiver components, and used optical parametric amplifiers to convert signals from 1.55  $\mu\text{m}$  to 3.8  $\mu\text{m}$  and back to 1.55  $\mu\text{m}$ .

## Acknowledgement

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## References

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2. J. R. Barry et al, J. Lightw. Technol., 10 (1992), 1939–1951.