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Penalty-free wavelength conversion with variable channel separation using gain-switched comb source ☆

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ABSTRACT

We demonstrate penalty-free all-optical wavelength conversion of 10.7 GBaud QPSK data using four-wave mixing and dual-correlated pumps derived from a gain switched comb source having large phase noise characteristics. We perform all-optical wavelength conversion over a 90 GHz bandwidth and show that the non-degenerate scheme is independent of the phase noise of the dual-pumps as long as they have correlated phase noise. The RF linewidth of the beat tone of the comb lines with separations up to 90 GHz is used to show excellent phase correlation between the comb lines. We obtain an error floor when all-optical wavelength conversion is performed using a single comb line from the gain-switched comb source as a pump in a partially degenerate scheme. The wavelength range for conversion is limited only by the spectral bandwidth of the gain-switched comb source.

0. Introduction

Optical frequency comb sources find applications in diverse areas such as optical communication, spectroscopy and metrology [1,2]. In optical communications, the comb sources are typically used for generating super channels, microwave carriers in RF over fiber and for the optical generation of OFDM signals [3–5]. Gain switching a semiconductor laser is one of the promising techniques used to design a compact optical comb source [6]. Gain-switched comb sources (GSCS) provide stability, spectral flatness and tunability in the free spectral range, thus making them suitable for applications in optical communication [6]. In this paper, we demonstrate the utility of these comb sources towards all-optical wavelength conversion of data. Wavelength conversion is one of the optical signal processing functionalities proposed to be implemented in the network nodes to allow dynamic and all-optical allocation of the wavelengths to users based on demand [7]. This functionality is performed through four-wave mixing (FWM) between the signal and a pump of suitable wavelengths in a nonlinear medium [7]. The FWM process is typically associated with an inherent phase noise transfer from the pump and the signal to the converted wavelength [8], thus requiring pump sources of very narrow linewidths for a penalty-free operation, especially for data in advanced modulation formats [9]. We had demonstrated the phase-noise retention scheme with the use of dual-correlated pumping in an earlier work [10]. In this work we show the practicality of the wavelength conversion scheme using dual-correlated pumps derived from a GSCS that has large phase noise on each comb lines, but with excellent phase correlation between them. The use of GSCS enables the design of a reconfigurable wavelength converter that allows conversion of data to a desired wavelength.

We demonstrate the wavelength conversion of data in quadrature phase shift keyed (QPSK) format using a fully coherent optical receiver. In Section 1, the phase correlation among the comb lines is shown by measuring the linewidth of the RF beat tone up to 90 GHz. In Section 2, we demonstrate penalty-free wavelength conversion of a 10.7 GBaud QPSK signal over a span of 90 GHz using comb lines from the GSCS, limited only by the spectral bandwidth of the GSCS. Since the impact of phase noise is more on lower baud-rate systems, the choice of 10.7 GBaud QPSK system is more relevant to the present study as compared to higher baud-rate systems.

1. Correlation of gain-switched comb source

When two optical signals (with frequencies f_{s1} and f_{s2} and phase noises $\Delta\theta_{s1}$ and $\Delta\theta_{s2}$) fall on a photodetector, the frequency

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of the RF beat tone is given by

$$f_{beat} = |f_{s1} - f_{s2}|, \tag{1}$$

and the phase error variance of the RF beat tone is

$$\sigma^2_{\Delta\theta-beat} = \sigma^2_{\Delta\theta-s1} + \sigma^2_{\Delta\theta-s2} - 2Cov(\Delta\theta_{s1}, \Delta\theta_{s2}), \tag{2}$$

where $\sigma^2_{\Delta\theta-beat}$ represents the phase error variance of the phase noise of two beat signals, f_{s1} and f_{s2} [11]. When the phase noise of the two optical signals beating in the photodetector are correlated, $Cov(\Delta\theta_{s1}, \Delta\theta_{s2}) = \sigma^2_{\Delta\theta-s1} = \sigma^2_{\Delta\theta-s2}$. Hence, when the comb lines are correlated, $\sigma^2_{\Delta\theta-beat}$ becomes zero thereby resulting in an RF beat tone with a delta-function lineshape.

1.1. *Experimental setup*

The schematic of the experimental setup that is used to measure the correlation of the comb lines is given in Fig. 1. The GSCS, similar to that outlined in reference [2], has comb lines separated by 15 GHz which are filtered using a programmable optical filter (Finisar WaveShaper 1000S, WS) and allowed to beat on a high-speed photodetector (PD) in order to measure the linewidth of each beat tone. The linewidth of the RF beat tones of the comb lines at the harmonics of 15 GHz up to 90 GHz is measured using an ESA with an external RF mixer.

1.2. *Results and discussion*

The results of the linewidth measurement of the RF beat tone of the GSCS lines are given in Fig. 2. The linewidth of the RF beat tone up to 90 GHz is found to be constant at 42 Hz (limited by the resolution of the ESA, the settings for which are shown in Fig. 2), thus proving that the GSCS has excellent correlation between the comb lines.

We use these gain-switched comb lines with excellent correlation to demonstrate penalty free wavelength conversion of 10.7 GBaud QPSK data.

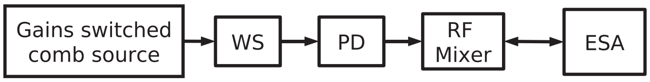

Fig. 1. Schematic of the experimental setup used to measure the correlation of the gain-switched comb lines up to 90 GHz separation.

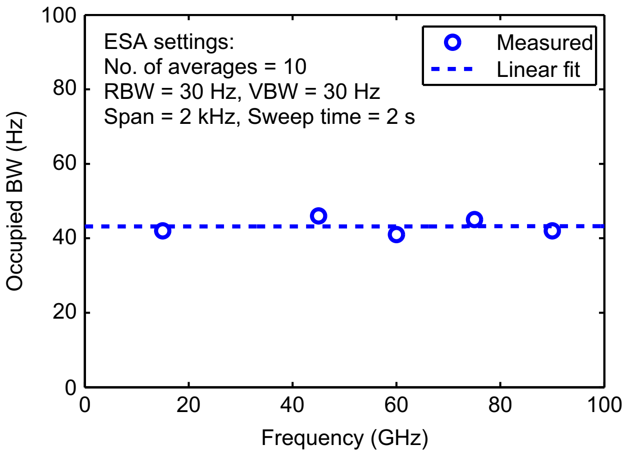

Fig. 2. Experimental results of RF beat-tone linewidth the gain-switched comb source up to 90 GHz.

2. All-optical wavelength conversion

FWM is typically implemented using partially degenerate or non-degenerate schemes. Mixing schemes are partially degenerate when the two mixing pumps have identical frequencies. In this scheme, the phase noise relationship between the pump (with a frequency f_{pump}), signal (with a frequency f_{signal}) and the wavelength converted signal (referred to as idler henceforth) with a frequency $2f_{pump} - f_{signal}$ is given by [8,10,12]

$$S_F(f)_{idler} = 4S_F(f)_{pump} + S_F(f)_{signal}, \tag{3}$$

where $S_F(f)$ represents the power spectral density (PSD) of FM noise [11]. When the two pumps have different frequencies, it is a non-degenerate scheme. Among these two schemes, the non-degenerate scheme is considered to be better because of its large and uniform conversion efficiency in addition to a very low polarization dependence [13,14]. When two independent pumps are used in the non-degenerate scheme, the phase noise of the idler is related to that of the two pumps (with frequencies f_{pump-1} and f_{pump-2}) and the signal as [15,10,12]

$$S_F(f)_{idler} = S_F(f)_{pump-1} + S_F(f)_{pump-2} + S_F(f)_{signal}. \tag{4}$$

The phase noise transfer puts a stringent requirement on the phase noise of the two pumps, especially when the wavelength conversion occurs at multiple nodes combined with the movement optical communication industry towards advanced modulation formats for higher spectral efficiency. However when the two pumps have correlated phase noise, the phase noise of the idler corresponding to the frequency $f_{idler} = \pm(f_{pump-1} - f_{pump-2}) + f_{signal}$ is given by [10,12]

$$S_F(f)_{idler} = S_F(f)_{signal}. \tag{5}$$

This result is independent of the individual phase noises of the pumps and thus eases the phase noise requirements on the pumps.

2.1. *Experimental setup*

The schematic of the experimental setup is shown in Fig. 3. The optical comb source used in this work consisted of a gain-switched single mode laser without any external injection or stabilization that generated a comb with about 8 lines, a spectral mode spacing of 15 GHz, and a linewidth of around 2 MHz on each comb line [2]. Light from this GSCS is passed through a WS to filter out the two desired comb lines. It is then amplified using an EDFA and used as the dual-correlated pumps. This is combined with the 10.7 GBaud QPSK signal using a 3 dB coupler and then passed through an isolator into a nonlinear SOA (CIP XN-OEC-1550). Polarization controllers (PC) are used before the signal and pumps are injected into the SOA for best conversion efficiency. The total power of the two pumps at the input of the SOA is 0 dBm and the signal power is adjusted to be 10 dB below the pump power to avoid bit patterning effects [16]. A bandwidth tunable passive optical filter is used to filter the signal/idler for analysis in the coherent receiver. The coherent receiver consists of a narrow linewidth external cavity laser acting as the local oscillator (LO), and an integrated coherent receiver with 90° hybrid and balanced photodiodes (Coh. Rx.). The signals at the output of the detector are captured using a real time scope for offline DSP.

The QPSK transmitter used in the setup consists of a pattern generator (PPG), generating data and data at 10.7 Gbits/s, corresponding to the I and Q channels respectively. The data consists of $2^7 - 1$ PRBS pattern, and data is delayed by 16 bits using a co-axial delay line (Delay), to decorrelate the I and Q channels. A noise loading stage with two EDFAs is used to change the OSNR (measured using an optical spectrum analyzer (OSA)) before the