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Research Letter

Demonstration of an All-Optical 2-to-4 Level Encoder Based on an Optical Parametric Amplifier

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We demonstrated a novel technique for all-optical 2-to-4 level amplitude-shift keying (ASK) coding based on a fiber optical parametric amplifier. A 20-Gb/s signal is realized by multiplexing two 10-Gb/s data streams.

1. Introduction

With growing internet, multilevel modulation has received great interest as the increasing demands of the transmission capacity of the optical fiber network while increasing WDM channels is limited by the spectral bandwidth. Multilevel modulation formats are effective ways to overcome such problems because of their higher information packing capacity in a single symbol, that is, coding multiple bits per symbol. Some schemes have been proposed [1–3] to achieve this goal. However, all of these schemes generated multilevel signal electronically, then modulated an optical carrier. Recently, some all-optical methods have been demonstrated to avoid the speed limitation of electronic components. For the multilevel phase-shift keying format, differential quaternary phase-shift keying (DQPSK) and 8-level PSK have been widely studied recently [4]. In order to further increase signal level, simultaneous modulation of amplitude and phase-shift keying (APSK) has been demonstrated [5]. On the other hand, multilevel ASK modulation is also an efficient way to realize higher bit rate in the communication system. Cross-polarization modulation (XPolM) has been explored in semiconductor optical amplifier (SOA) for multilevel modulation implementation [6]. However, this approach requires a dedicated setting polarization-state angle of input waves in SOA.

In this paper, we present experimental demonstration of 4-level ASK at 20 Gb/s using an optical parametric amplifier (OPA). The great triumph of using fiber-based OPA was its inherent femtosecond respond time governed by the $\chi^{(3)}$ nonlinear susceptibility of an optical fiber [7] and potential signal gain. The sole use of OPA effects in our setup makes it a possibility for higher speed operation.

2. Principle

Amongst nonlinear effects induced by $\chi^{(3)}$ nonlinear susceptibility in silica, one of the important phenomena is four-wave mixing (FWM). FWM is also a nonlinear effect that leads to OPA, as a special case of which the waves satisfy the phase matching conditions. In the degenerate FWM case [7], two frequencies of light at ω_p and ω_s copropagate in a nonlinear medium, then a new frequency component, ω_i, can be generated, satisfying $\omega_i = 2\omega_p - \omega_s$. During this process, the interplay between FWM, self-phase modulation (SPM), and cross-phase modulation (XPM) effects can lead to an exponential amplification if ω_p is a high-power pump and ω_s is a weak probe. This resultant exponential amplification is known as OPA. However, ω_p, ω_s, and ω_i are named pump, signal and idler, respectively, as shown in Figure 1. The dashed line represents the gain spectrum of OPA. This optical amplification is achieved by choosing the frequencies of interplaying waves such that they satisfy a phase-matching condition optimal for an exponential gain in power on the signal, and the idler. In the specific case of single pump, OPA occurs at regions satisfying $-4\gamma P_P < \Delta\beta < 0$, where $\Delta\beta = 2\beta(\omega_p) - \beta(\omega_s) - \beta(\omega_i)$, and $\beta(\omega)$ is the propagation constant as a function of frequency, γ is the nonlinear coefficient, P_P is the pump power.

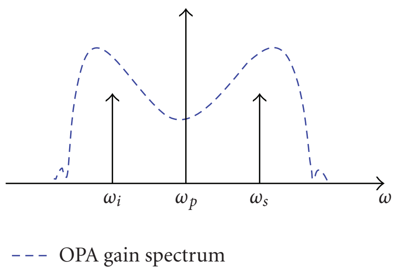

Figure 1: Schematic of OPA.

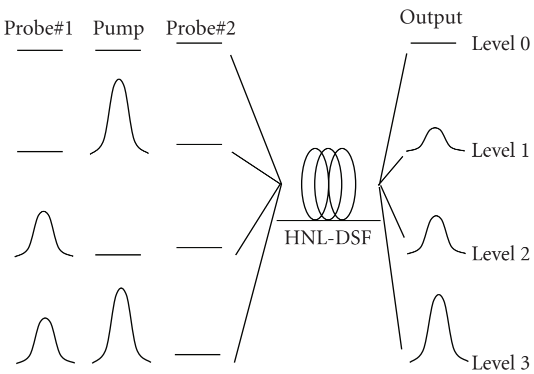

Figure 2: The operating principle of multilevel encoding.

In order to achieve highly efficient OPA, the phase-matching condition should be satisfied by setting appropriate wavelengths of pump and signal. Assuming an undepleted pump, parametric gain $G_s \gg 1$, and phase-matching condition is satisfied, G_s can approximately be obtained in decibel as [7]

$$G_s \approx 10 \log\left(\frac{1}{4}\exp\left(2\gamma P_P L\right)\right), \tag{1}$$

where L is the fiber length. It shows that the parametric gain is exponentially dependent on the pump power.

The principle of the proposed multilevel encoder is shown in Figure 2. Three waves were launched into a spool of highly nonlinear dispersion-shifted fiber (HNL-DSF) as the nonlinear medium. Two of them were amplitude modulated with pseudo-random bit sequence (PRBS) as a pump and probe number 1, respectively. The third one, probe number 2, was a continuous-wave (CW). When the pump and probe number 1 are "0," only the probe number 2, low CW power comes out, this is the first level. When the pump is "1" and the probe number 1 is "0," the probe number 2 can be amplified to the second level by OPA process. When the pump is "0" and probe number 1 is "1," the power comes out from fiber is the sum of probe number 1 and probe number 2 which is higher than the second level and forms the third level. Finally, when the pump and probe number 1 are both "1," the sum of probe number 1 and probe number 2 can be amplified together, resulting in the strongest power and the fourth level. Then, the two data streams information can be transferred and 4-level ASK encoding was realized through OPA effect.

3. Experimental Setup

Figure 3 shows the experimental setup. The nonlinear medium used for OPA was a spool of 1 km HNL-DSF with nonlinear coefficient $\gamma \approx 14\,W^{-1}km^{-1}$ and zero-dispersion wavelength $\lambda_0 \approx 1560$ nm. The two input 10-Gb/s return-to-zero (RZ) signals were generated by coupling two tunable laser sources, TLS1, with wavelength λ_{pump} at 1561 nm and TLS2 with wavelength $\lambda_{probe\sharp 1}$ at 1545.5 nm using a 3-dB coupler. They were launched into two external Mach-Zehnder intensity modulators (MZ-IM) for return-to-zero on-off keying (RZ-OOK) modulation, as pump and probe number 1. The two MZ-IMs were driven by 10-Gb/s 2^{31}-1 PRBS and 10 GHz clock, respectively. Then the pump and probe waves were split by a WDM coupler, WDMC1, after amplitude modulation. The pump wave was then amplified to 20.4 dBm by two erbium doped amplifiers, EDFA1 and EDFA2 at EDFA2 output. A 0.8-nm bandwidth tunable band-pass filter, TBPF1, was inserted between two EDFAs to reduce amplified spontaneous emission (ASE) noise at the input of EDFA2. On the other branch, the probe number 1 wave was boosted by EDFA3 to 11 dBm after passing through a 0.8 nm TBPF2 to reduce the noise and optical delay line (ODL) to align the pattern of pump and probe. Then, these two branches were combined by WDMC2. The probe number 2 from the third tunable laser source, TLS3, with input power of HNL-DSF at 0.5 dBm and wavelength $\lambda_{probe\sharp 2}$ at 1545.9 nm, was shifted 0.4 nm from $\lambda_{probe\sharp 1}$ to avoid interference. TLS3 was combined with the output of WDMC2 using a 3-dB coupler and the polarization controller, PC4, was used to adjust state of polarization (SOP) of probe number 2 to obtain maximum gain. The probe number 1 and probe number 2 propagated through the HNL-DSF together to experience OPA effects. The 0.8 nm TBPF3 placed after HNL-DSF, set at 1545.5 nm, was used to filter out the multilevel signal. The TBPF3 output port was monitored by a digital communication analyzer (DCA). The variable optical attenuator (VOA) before DCA was used to prevent damage.

4. Results and Discussion

The waveforms of coding process are showed in Figure 4, which represent the 4-level data patterns in time domain at 1545.5 nm. According to the encoding principle, the upper and middle patterns are level 1 and level 2 versus level 0, respectively. All 4-level can be identified in the bottom of Figure 4. As demonstrated in Figure 2, the upper pattern was a duplicate of pump pattern. The middle pattern was probe number 1 signal. Then the bottom pattern consisted of the above two. Figure 5 is the corresponding eye diagram. It was found that the level spacing can be arbitrary but we chose around 0 : 1 : 2 : 4 for clear identification [8]. The extinction ratio of the three separated 2-level eye patterns corresponding to level 1, 2, and 3 were 7.56 dB, 11.07 dB, and 13.18 dB, respectively. While the respective signal-to-noise ratios (SNR) were 18.01 dB, 26.31 dB, and 26.56 dB. As the lowest amplitude, the performance of level 1 was relatively weaker than that of the other two due to the existence of

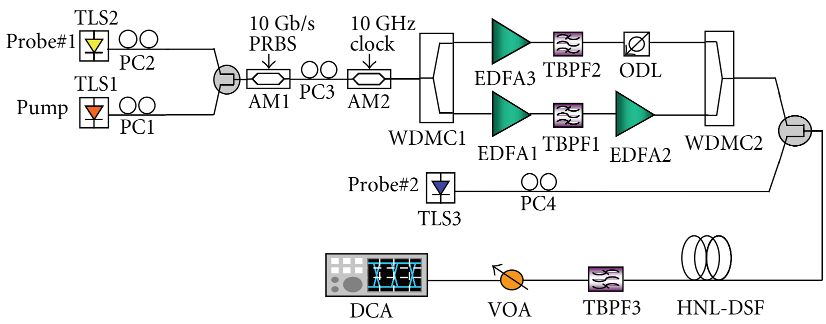

Figure 3: Experimental setup of multilevel encoder.

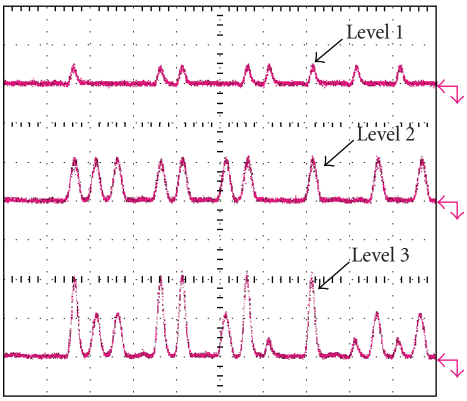

Figure 4: The waveforms of 4-level signal. Time base: 200 ps/div.

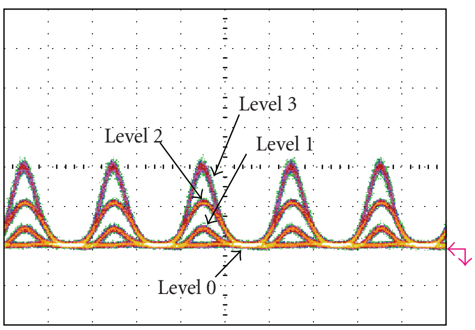

Figure 5: Eye diagram of 4-level signal. Time base: 50 ps/div.

the CW. The narrower pulsewidth of levels 1 and 3 whose operation principle was like an AND gate due to pulse compression in FWM process [9]. The mark level of level 3 was noisier than the other levels due to the ASE from EDFA amplified by OPA effect.

Furthermore, note that the scheme we proposed here can also be potentially applied to an all-optical digital-to-analog conversion (DAC) system [10]. The incoming serial pulses which represent a digital signal are converted to the parallel pulses by an optical serial-to-parallel converter [11]. The parallel pulses are assigned to the probe and pump as the most significant bit (MSB) and the least significant bit (LSB), respectively. So as indicated in Figure 2, the 2-bit digital signals "00," "01," "10", and "11" correspond to the analog signals "0," "1," "2", and "3". Consequently, a 2-bit all-optical DAC scheme with binary code can be realized. The advantage of this technique is its easy implementation and flexibility of level spacing optimization.

5. Conclusions

We have experimental demonstrated a novel technique for all-optical 2-to-4 level ASK coding based on OPA. A conversion from two optical RZ-OOK 10-Gb/s signals to a 4-level ASK signal at 20 Gb/s was achieved. The results in this paper have demonstrated that this device has potential usage in improving the performance of the available channel in WDM communication system. Thus, the proposed scheme provides a new way to increase the speed of optical network and meets the growing demand of the internet in future.

The results also exhibit that this device can be applied in all-optical DAC system potentially. This propose is left for future work.

Acknowledgments

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