All-Optical Wavelength Conversion of a Chaos Masked Signal

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***Abstract*—Wavelength conversion in the transmission of a message masked by optical chaos is experimentally demonstrated. In our setup, chaos is generated by a distributed-feedback laser subject to delayed optical feedback, and hides a message by additive chaos masking. The optical wavelength is converted, along the transmission line, by four-wave mixing in a semiconductor optical amplifier. At the receiver, the message is extracted by master–slave synchronization. Our experiments demonstrate that secure communications based on chaos are compatible with channel switching as required in reconfigurable optical networks.**

***Index Terms*—Chaos, cryptography, frequency conversion, optical fiber communication, optical signal processing.**

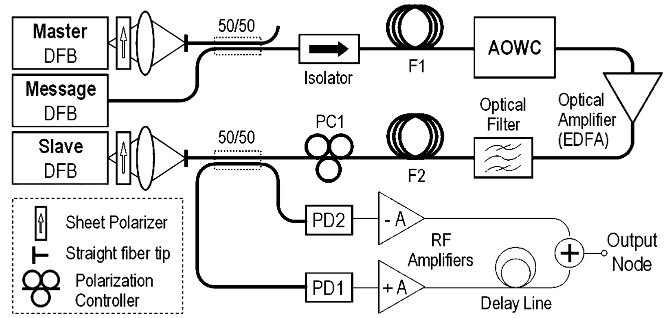

Fig. 1. Experimental setup for chaos synchronization. The AOWC block contains the elements required for wavelength conversion (see Fig. 2).

I. INTRODUCTION

OPTICAL chaos cryptography is a hardware technique for secure transmission based on the synchronization of a pair of matched chaotic lasers in a master–slave configuration [1]–[3]. After initial investigations on basic principles, more recent work has been focused towards the application of chaotic cryptography in real networks. Message relay [4] and broadcasting [5], as well as dual-channel [6] and wavelength-division-multiplexing [7] operation have already been demonstrated.

An important requirement for compatibility with existing reconfigurable networks is optical channel switching. In this letter, we demonstrate the detection of a chaos-masked subcarrier after wavelength conversion by four-wave mixing (FWM) in a semiconductor optical amplifier (SOA). Message extraction is achieved by properly tuning the slave to match the new received wavelength, both in back-to-back experiments as well as after propagation along a 100-km fiber.

II. EXPERIMENTS

A. Experimental Setup

The experimental arrangement is shown in Fig. 1. The setup is based on a closed-loop short-cavity master–slave configuration operating in the generalized synchronization regime. Both master (ML) and slave (SL) are driven to chaos by back-reflection from the tip of the launching fiber [8], defining a 5-cm external cavity. This laser pair consists of 1-mW DFB devices selected between first neighbors of the same wafer. Their wavelengths ($\lambda \approx 1540$ nm) have been matched within 0.1 nm by adjusting the temperature, and then finely tuned until they lock by injection. Polarizers in front of the lasers select the same polarization of the laser emission for feedback and injection.

The subcarrier is applied by a third DFB laser, in a standard additive chaos masking scheme. To prevent the message laser from disturbing the master, their unperturbed emission wavelengths differ by about 75 pm, so that the message is embedded within the optical spectrum of the master when it becomes chaotic. This solution has been preferred for this first demonstration because it is easy to implement experimentally, though chaos shift keying or chaos modulation schemes [1], [2], [8] would offer a better security level. As usual, the message is recovered by subtracting, from the received signal (message + masking chaos), the chaos generated by the synchronized SL. The path between transmitter and receiver includes an optical isolator to ensure unidirectional injection, two spans of single-mode fiber (spool F1 and F2 in Fig. 1), and possibly an optical amplifier to compensate for the fiber attenuation. In back-to-back experiments, spools F1 and F2 consist of just a few meters of standard single-mode fiber and the optical amplifier is not present.

The all-optical wavelength-conversion block (AOWC in Fig. 1), based on the FWM process in an SOA, is described in detail in Fig. 2. The required components are simple, relatively low-cost, and suitable for high bit-rate transmission [9]. An amplified external cavity laser (ECL) generates the pump for the FWM. The incoming signal to be converted and the pump are launched into the SOA by means of a 50/50 coupler.

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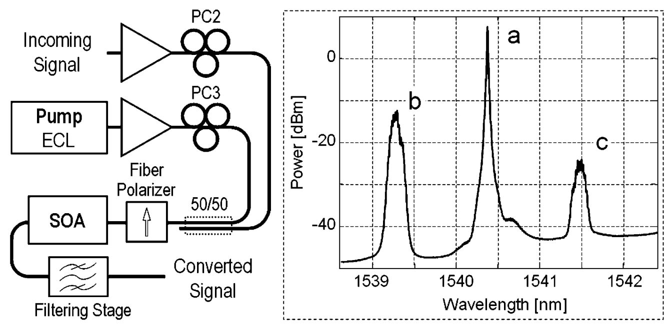

Fig. 2. Experimental setup for the AOWC block. The graph reports the optical spectrum at the SOA output, before the filtering stage, with the different contributions at the wavelengths of (a) pump, (b) original master, and (c) converted master.

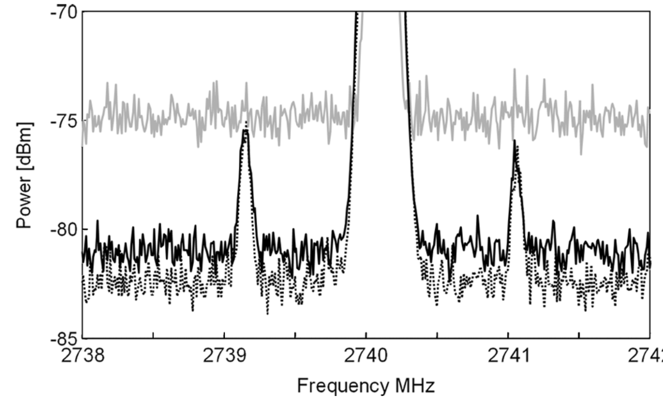

Fig. 3. RF spectra at the system output for a 1-MHz sinusoidal message modulating an RF subcarrier, in a back-to-back experiment: ML and SL "OFF" (dashed black line); ML "ON" and SL "OFF" (gray line); ML and SL "ON" and aligned (continuous black line).

Both beams are polarization controlled in order to guarantee the best FWM efficiency. The selected SOA has an emission center-wavelength of 1550 nm and a 1.5-mm-long active region, specifically designed for nonlinear operations. During the experiments, the SOA input current is 450 mA, well above its threshold $I_{\rm th} \approx 260$ mA. As shown in the graph of Fig. 2, degenerate FWM between pump and original master beams yields the converted master beam, with an efficiency of about -10 dB (measured as the ratio between the SOA output power at the wavelength of the converted and original master beams) and a conversion range of 20 nm. At the SOA output, a filtering stage removes the residual power contributions at the wavelengths of the pump and original master [(a) and (b) in the graph of Fig. 2]. Here, a cascade of two filters ($\Delta\lambda_{(-3\ {\rm dB})} \approx 0.8$ nm and $\approx$0.12 nm) is used for better rejection.

Before inserting the conversion block, ML and SL have been synchronized by adjusting their pump currents (about 50% above threshold) and their temperature, as well as the injected and the feedback power (both of the order of 1% of the laser output power), and by finally matching their external cavity lengths. The chaotic regimes of ML and SL are compared, by observing the outputs of photodiodes PD1 and PD2 in the frequency domain with an RF spectrum analyzer. The synchronization level is evaluated, as explained in [8], by observing the spectrum of the difference of ML and SL outputs. The delay line shown in Fig. 1 is required for compensation of the differential propagation delay [8]. Following this setup optimization in a straight back-to-back configuration, we have obtained a correlation coefficient between master and slave outputs $\rho \approx 0.9$ for a chaos bandwidth of about 5 GHz, limited by photodiodes and RF amplifiers.

Successively, the conversion block of Fig. 2 has been inserted. The induced shift of the master wavelength has been selected as a trade-off between the requirement of filtering out the unwanted contributions at the master and pump wavelengths, and that of tuning the SL to match the central wavelength of the converted signal. Thus, a shift of 2.25 nm has been introduced, and the SL has been tuned accordingly by acting on its temperature controller ($\Delta T = 25$ K).

After wavelength conversion, the whole setup has been aligned to maximize chaos cancellation, i.e., the difference of chaos amplitude at the system output, in two conditions: with ML ON, SL OFF (for masking) and ML ON, SL ON and synchronized (for message extraction).

Such optimization has been performed for two cases: around 500 MHz and around 2.74 GHz, i.e., the frequencies where we intended to locate the subcarrier in the transmission experiments. In both cases, a chaos cancellation of the order of 8 dB ($\rho \approx 0.85$) was achieved in optimized conditions, with a reduction of about 3 dB with respect to that measured without wavelength conversion.

B. Back-to-Back Transmission Experiments

As a first step, we have performed back-to-back transmission experiments, with in-line wavelength conversion, of a message, consisting of a sinusoid at 1 MHz over a subcarrier at about 2.74 GHz. In Fig. 3, we show the RF spectra measured at the output of the system. The signal without masking (ML and SL OFF) corresponds to the dashed black trace. The selected amplitude modulation (AM) index yields sidebands completely covered by chaos when the ML is ON (gray trace). In this condition, the signal-to-noise ratio (SNR) for the message is approximately 0 dB; thus, the message is effectively hidden. Finally, when the slave is also switched ON, and aligned, the AM sidebands are extracted from chaos (continuous black trace), and SNR on the sidebands results are only slightly reduced (about 1-dB penalty) with respect to that of the original message.

C. Transmission Experiments Along a Fiber-Optic Link

We have then carried on transmission experiments along a fiber-optic link inserted between ML and SL and we have demonstrated signal recovery of a 500-MHz subcarrier after 100-km propagation, with in-line wavelength conversion. In this scheme, each spool (F1 and F2 in Fig. 1) consists of a 50-km span of commercial nonzero dispersion-shifted fiber [(NZDSF) ITU G.655] with an attenuation coefficient $\alpha \approx 0.22\ {\rm dB} \cdot {\rm km}^{-1}$ and chromatic dispersion $D \approx 4\ {\rm ps} \cdot {\rm nm}^{-1} \cdot {\rm km}^{-1}$ at 1.55 μm. Wavelength conversion occurs through the SOA at the midspan point, and also ensures complete compensation of the chromatic dispersion, which, however, plays a minor role because of the relatively narrow chaos bandwidth.

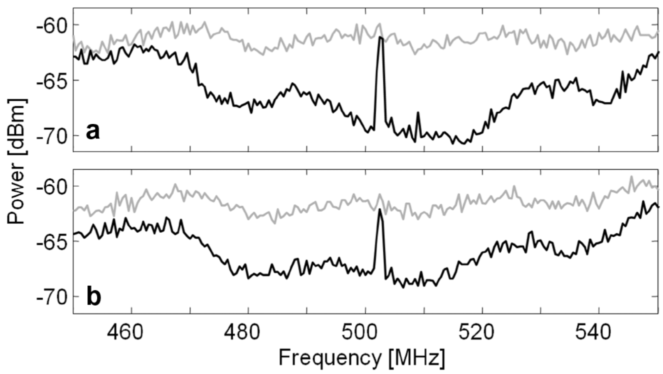

Fig. 4. RF spectra at the system output of the 500-MHz subcarrier extracted in the master–slave difference (black traces) and masked by the chaotic master (gray traces): (a) in back-to-back configuration; (b) after propagation along a 100-km link of NZDSF.

Whereas in a back-to-back scheme, performed for comparison, the SNR of the recovered subcarrier (limited by residual chaos) was of about 8 dB [Fig. 4(a)], after propagation through the fiber, the SNR was significantly reduced. This drawback seems mainly due to the amplified spontaneous emission noise of the optical amplifier (introduced to compensate for the propagation losses), which disturbs the SL, thus decreasing the synchronization level. Inserting an optical filter (Fig. 1) effectively improves chaos cancellation and an SNR of about 6 dB has been finally obtained [Fig. 4(b)].

III. Discussion of Results

In our setup, a temperature variation of 25 K has been introduced, which is expected to significantly modify the parameters of the SL. To investigate this point, simulations have been carried on using the Lang–Kobayashi (L-K) model, with a typical parameter set ([10], $\alpha = 3.2$ for our lasers), and assuming a dependence of parameters α, G (gain), N_0 (carrier concentration at transparency) with temperature as reported in [11]. It has been found that temperature variations of parameters partially compensate one another, so that synchronization (thus, correlation coefficient and chaos cancellation) is only slightly reduced by the temperature change. Both numerically and experimentally, it is found that compensation can be improved by properly adjusting both supply current and injection. On the other hand, two lasers with an intrinsic mismatch of parameters of the same amount ($\approx 7\%$) cannot synchronize, as expected. Since the compensation quality depends on laser parameters, a selection on different matched pairs will be required to find the most suitable for this wavelength conversion scheme. A practical limitation will finally come by the allowable temperature range to set the wavelength of the lasers.

Another important theoretical issue to be considered is the impact of the phase reversal, produced by FWM, on synchronization. This effect has also been numerically evaluated by the L-K model. We found that changing the sign of the phase of the term, describing injection from master into slave, does not prevent synchronization in specific spectral regions. Chaos cancellations of 10–15 dB on bandwidths of a few hundred megahertz have been found, provided that the external parameters of the lasers are accurately set, as well as the injection level. Moreover, the time delay between master and slave (which is clearly identified by calculating their correlation) has to be compensated: such optimization of external parameters and delay is the standard procedure performed in all synchronization experiments.

In conclusion, we have demonstrated the recovery of a chaos-masked subcarrier, which has been wavelength-converted by means of FWM in an SOA. Successful chaos-cancellation and signal extraction has been performed in a back-to-back scheme and also after propagation along a 100-km fiber-optic link, with in-line wavelength conversion. Optical phase conjugation, widely used to perform compensation of dispersion and nonlinearity [12] in fiber-optic links, thus appears to be compatible with this secure transmission scheme.

Further experimental and theoretical investigations will be devoted to evaluate channel switching of digital signals in baseband.

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