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Private communication using chaotic light

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Synchronized chaotic lasers both encode and decode information, potentially providing a reliable alternative to conventional secure networks.

A major advantage of broadband carriers is that they enhance the robustness of communications channels to interference from narrowband disturbance. This technology is the basis, for example, of spread-spectrum communication methods such as the code division multiple access protocol, which combines high-bandwidth digital information with a pseudorandom digital code. The result is a hard-to-interfere-with signal that is useful in military applications such as antijamming and secure messaging. So-called chaos-based communications[1–3] is also a broadband technique, but it is based on a different concept. Here, the carrier is a chaotic (seemingly erratic but fully described by deterministic equations) analog optical waveform, generated at the physical layer. The message is encoded in such a way that the information is hard for an eavesdropper to extract. Decoding by the appropriate receiver requires synchronizing the carrier. The receiver architecture performs a nonlinear filtering process[4] that is then used to subtract the encoded, transmitted information (see Figure 1). Chaos-based communications was proposed and demonstrated in the early 1990s in electronic circuits, and soon extended to optical systems.[2–7]

Photonics provides simple ways of generating high-dimensional chaotic carriers that offer both a substantial level of security and the possibility of excellent transmission rates. The simplest way to generate a chaotic optical carrier is to employ a semiconductor laser and feed back part of the emitted light into the device after a certain time delay (the all-optical approach). Alternatively, the light can be transformed into electrical current and, after a certain time delay, be used to feed, either the laser bias current or an external modulator (the electro-optical approach). Early laboratory experiments demonstrated successful back-to-back communications in both all-optical[8] and electro-optical systems,[9] where high bit rates were achieved.

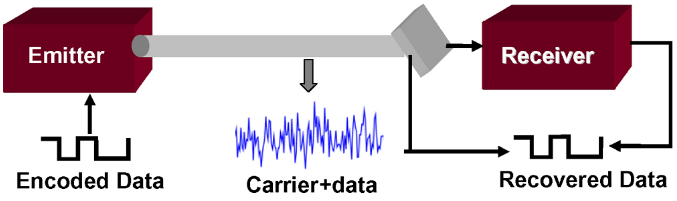

Figure 1. Schematic representation of the encoding/decoding process.

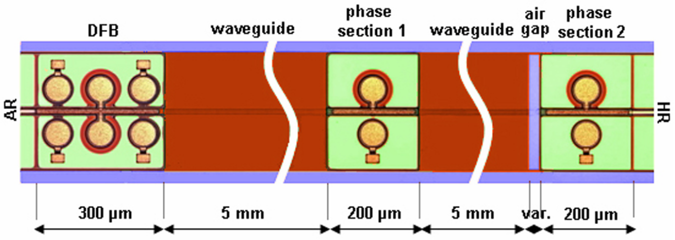

Figure 2. Photograph of the proposed integrated device for chaos generation, synchronization, and message encoding. AR (HR): Antireflection (high-reflection) coating. DFB: Distributed feedback laser.

In all-optical chaos-based communication systems, the emitter architecture is usually composed of a semiconductor laser subject to optical feedback from an external mirror. The receiver system, which has to match the emitter system, can operate subject to the same feedback loop (closed-loop scheme) or without optical feedback (open-loop scheme). The open-loop configuration is mechanically more stable and easy to implement. It is also very robust against frequency detuning and small parameter mismatch. The closed loop is less stable, and the feedback cavities of the emitter and receiver must be matched with sub-wavelength precision, otherwise synchronization quality is very poor.[2] For these reasons, receivers with open-loop architecture are generally used in demonstrations. However, recently we realized that the closed-loop scheme allows for smaller message amplitudes, which provides higher security.[10] Integrated sources with delayed feedback promise higher stability and easier implementation of the closed-loop scheme.

Different techniques have been proposed to encode the information into the chaotic carrier. Better-known methods include

Continued on next page

chaos shift keying (the message is added by slightly modulating the injection current of the laser), chaos modulation (the message is incorporated by externally modulating the chaotic carrier), and additive chaos masking (the message is externally added to the chaotic carrier). After more than 10 years of research, the first field experiment occurred in a metropolitan area network in Athens, Greece, and was reported in 2005 by us and others[11] as the main outcome of the European project OCCULT.[12] In this experiment, chaotic fiber-optical communication over long distances (more than 100km) was achieved, with high transmission rates (>1Gb/s) and low bit-error rates (BERs) ($<10^{-6}$). The system used matched pairs of semiconductor lasers as chaotic emitters and receivers and off-the-shelf fiber-optic telecommunication components.

After achieving this important milestone, we tackled the development of mechanically stable integrated and hybrid sources, mainly through a European consortium under the PICASSO project.[13] Within this initiative, a novel photonic monolithic integrated device, consisting of a distributed feedback (DFB) laser, a passive resonator, and active elements that control the optical feedback properties, was designed, fabricated, and evaluated as a compact potential chaotic emitter in optical communications.[14] Different operating regimes, including stable solutions, periodic states, and broadband chaotic dynamics, were identified.

More recently, we designed, developed, and tested a new integrated device. The integrated optical source is composed of a DFB laser, two passive sections, two phase sections, and a narrow (2–10μm) air gap (see Figure 2). This new device provides high-bandwidth chaotic emission and the flexibility to change some parameters, which not only facilitates synchronization between emitter and receiver but also increases security. Figure 3 clearly shows the chaotic properties of the dynamics generated by the air-gap modules. The black line in Figure 3(a) is the radio frequency spectrum of the emitter, characterized by its breadth and large bandwidth. The inset details the time traces of the emitter and receiver lasers under synchronization conditions. The low power of the difference spectrum (blue line) proves excellent synchronization. Finally, we tested a back-to-back digital signal transmission using two similar integrated devices. A pseudo-random non-return to zero bit sequence at 1Gb/s was applied to the master input by using an external amplitude modulator (chaos modulation technique). We performed signal decoding at the receiver by measuring the chaos cancellation. Besides an efficient masking with BER ~0.5 (not shown in the figure), a clearly readable decoded message was obtained: see Figure 3(b).

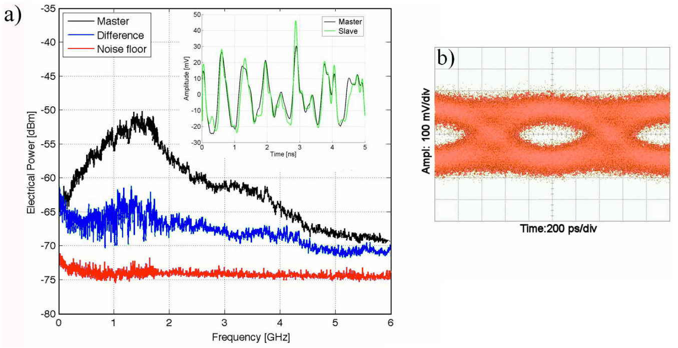

Figure 3. *(a) Power spectrum of the emitter laser (black line), difference between emitter and receiver power spectra under synchronized conditions (blue line) and noise floor (red line). (b) Recovered eye diagram of a 1Gb/s non-return to zero random sequence. mV/div: Millivolt per division. ps/div: Picosecond per division.*

Now that reliable sources have been developed and tested, we are focusing our research on long-distance transmission studies and all-optical signal processing based on delay-coupled photonic systems. For long-distance transmission, integrated all-optical sources and electro-optical hybrid devices, different encoding schemes, and dense-wavelength-division multiplexing techniques are being combined with the aim of reaching 10Gb/s rates with low BERs ($<10^{-12}$). For photonic signal processing, new concepts are currently being developed. A European project (PHOCUS) aims to design and implement a photonics realization of a liquid-state machine,[15] with the potential for versatile and fast signal handling. Such a device represents an alternative approach to computation. Thetarget is to achieve high computational performance with only a small number of photonics components, using dynamical systems with time delay to realize complex classification tasks.

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10.1117/2.1201002.002614 Page 3/3

Claudio Mirasso is a full professor and a researcher. He has authored or co-authored over 140 publications. His research interests include instabilities, synchronization and control of chaotic semiconductor lasers, and dynamics and applications of delayed coupled systems.

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