Optical Communication with Chaotic Waveforms

Gregory D. VanWiggeren and Rajarshi Roy*
School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430
(Received 29 April 1998)

A high-dimensional chaotic waveform is generated by driving an erbium-doped fiber-ring laser with a digital information signal applied to an intraring electro-optic modulator. We show that a receiver with appropriately matched configuration, time delays, and relative amplitudes is able to recover the information signal, consisting of pseudorandom bits at 126 Mbits/sec, from the chaotic carrier. We also examine how recovery of the information fails when the receiver parameters are mismatched. [S0031-9007(98)07368-2]

PACS numbers: 89.70.+c, 05.45.+b, 42.55.–f

A chaotic carrier of information can be considered a generalization of the more traditional sinusoidal carrier. In communication systems which use chaotic waveforms, as in many more conventional methods, information can be recovered from the carrier using a receiver which is "tuned," or synchronized, to the dynamics of the transmitter. Communication methods using chaotic carriers have been studied for the past few years, and several methods have been experimentally demonstrated in electronic circuits [1].

While chaotic electronic circuits typically have bandwidths of 100 kHz or less [2], the optical system presented here has a bandwidth of at least several GHz. In those electronic chaotic communication methods that have been demonstrated, the chaos usually has been low dimensional. For certain low-dimensional chaotic communication methods, it has been shown previously that the message can be extracted from the transmitted signal by reconstructing the system's chaotic attractor [3]. A communication method utilizing higher dimensional chaos is likely to provide enhanced privacy. Numerical analysis of our experimental data indicates that the dynamics of our system are indeed high dimensional, of order 10 or greater.

Previously, Goedgebuer and colleagues have demonstrated chaotic communication of a 2 kHz sine wave using a hybrid electro-optic system to generate high-dimensional chaotic fluctuations in wavelength [4]. Also in earlier work, we injected a small 10 MHz square wave optical message into a ring laser producing high-dimensional chaotic light. The square wave message was masked by the chaotic intensity fluctuations of the light from the ring laser as it propagated to a receiver, where the message was recovered [5].

Here we describe several qualitatively new developments, in both concept and technique, over previous work. Rather than using the chaotic light to mask a message, an intracavity intensity modulator is used to directly encode the message onto an optical chaotic carrier. Unlike our previous work, the message signal does not have to be small compared to the carrier or slow compared to the bandwidth of the laser fluctuations; they can have comparable bandwidths. The message modulation drives the chaotic dynamics of the laser. The laser dynamics, in turn, incorporate the digital message into the chaotic waveform. Both transmitter and receiver have configurations that involve two separate time delays, thereby enhancing the privacy of the transmission—successful recovery of the message depends on multiple parameter settings and a matched geometric configuration in the receiver. Finally, the receiver utilizes the polarization properties of the light to recover the digital information by dividing two signals, rather than taking a difference. These innovations enable us to demonstrate recovery of a pseudorandom sequence of bits at 126 Mbits/sec, limited by the bandwidth of our photodiodes. Placing a 1.5 km communication channel between the transmitter and receiver did not cause any obvious degradation of performance.

The experimental setup of the fiber-optic system is shown in Fig. 1. The inner ring of the transmitter includes EDFA 1 (erbium-doped fiber amplifier) and a polarizing lithium niobate ($LiNbO_3$) intensity modulator which encodes the message onto the chaotic light. The inner ring is approximately 40 m in length. The outer loop contains EDFA 2, to adjust the amplitude of the light field, and a polarization controller. The polarization controller consists of three wave plates ($\lambda/4$, $\lambda/2$, and $\lambda/4$, respectively) which allow control over the relative phase and polarization of the light fields in the inner ring and outer loop. The outer loop itself is approximately 36 m long and provides a time delay between these light fields.

Light coupled out of the transmitter propagates through a fiber-optic communication channel to the receiver. Ten percent of the transmitted light is sent through an attenuator to photodiode *A* (3-dB roll-off at 125 MHz). The length of the fiber in the outer loop of the receiver has been matched to the length of the transmitter's outer loop. The time delay between reception of a signal at photodiode *A* and reception at photodiode *B* (also 3-dB roll-off at 125 MHz) has been matched to the round-trip time in the inner ring of the transmitter. The signals detected by the photodiodes are recorded by a digital sampling oscilloscope at a rate of 1×10^9 samples/sec.

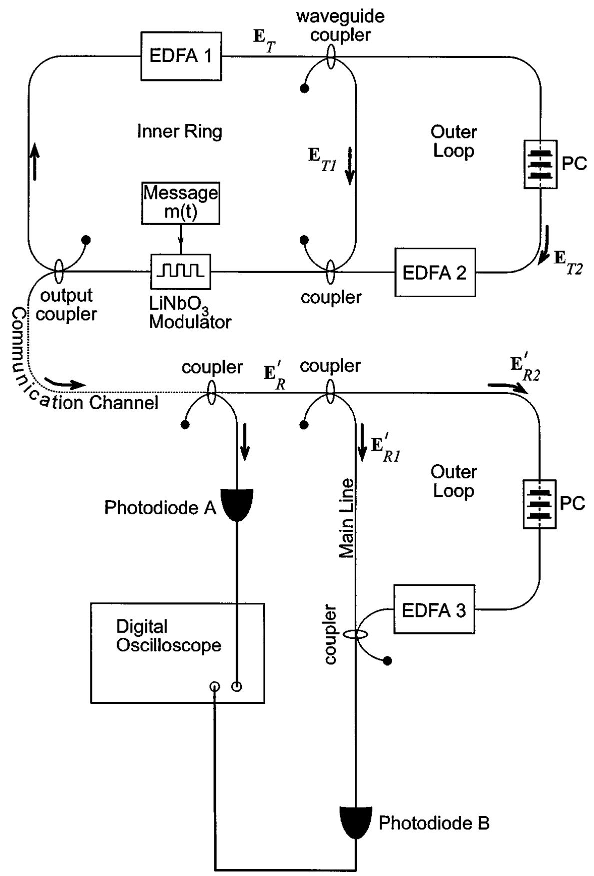

FIG. 1. Experimental system for optical chaotic communication. The message is encoded onto the chaotic lightwaves produced by the transmitter and sent via the communication channel to the receiver. Proper configuration, time delays, and power levels in the receiver allow recovery of the message. PC: polarization controller.

The transmitter in our system actually comprises two coupled ring lasers. The inner ring is one of these lasers; the other is formed partly by the inner ring and partly by the outer loop. A solitary erbium doped fiber ring laser (EDFRL) naturally produces chaotic fluctuations of intensity at frequencies ranging to many gigahertz and perhaps higher. Numerical models of the chaotic dynamics of EDFRLs have been developed which suggest that the dynamics of an EDFRL can be very high dimensional [6]. The chaotic dynamics are the result of the combination of nonlinearities in the amplifier and a round-trip time delay. While the nonlinear effects in the amplifier of a solitary EDFRL are sufficient to induce chaotic intensity fluctuations, they do not significantly change a waveform from one round trip to the next. However, introducing the outer loop and its additional time delay into the transmitter causes the chaotic waveforms to change significantly after one round trip around the inner ring. Thus, any signals encoded onto the chaotic light by the $LiNbO_3$ modulator very quickly become incorporated into the chaotic dynamics of the transmitter. In this way, the information signal both modulates the chaotic lightwave and drives the chaotic dynamics of the transmitter, ensuring high dimensionality. Using a recorded time-series sequence of 250 000 points acquired at a rate of 1×10^9 samples/sec, we have numerically analyzed the transmitted waveforms using a false-nearest-neighbors algorithm [7] to estimate the global dimensionality of the attractor. The analysis indicated that the dimensionality of the dynamics is of order 10 or greater.

For simplicity in the discussion that follows, we do not consider the relative amplitudes of the waveforms. The discussion, instead, will focus on the effects of the time delays in the transmitter and receiver.

Light just after EDFA 1 in the transmitter's inner ring can be represented as a quasimonochromatic electric field

$$\mathcal{E}_T(z,t) = \mathbf{E}_T(z,t)e^{i(\omega t - kz)}, \tag{1}$$

where $\mathbf{E}_T(z,t)$ is a complex, slowly varying envelope that describes a chaotic waveform, and ω is the optical frequency. As the lightwave passes through the waveguide coupler, it splits into two parts. The part in the inner ring is called $\mathbf{E}_{T1}$. At the next coupler, light from the outer loop $\mathbf{E}_{T2}$ is added to $\mathbf{E}_{T1}$. That sum $\mathbf{E}_{T1} + \mathbf{E}_{T2}$ enters the modulator where a message is encoded onto it. The result is $m(t)(\mathbf{E}_{T1} + \mathbf{E}_{T2})$, where $m(t)$ is the message being transmitted at that time. At the output coupler, 10% of $m(t)(\mathbf{E}_{T1} + \mathbf{E}_{T2})$ is transmitted to the receiver via the communication channel. Ninety percent stays in the ring and passes through EDFA 1 to produce $\mathbf{E}'_T \cong m(t)(\mathbf{E}_{T1} + \mathbf{E}_{T2})$; we note that the field is amplified but the shape of the envelope is not changed significantly. After another round trip through the inner ring, $m(t+\tau)(\mathbf{E}'_{T1} + \mathbf{E}'_{T2})$ is transmitted, where τ is the round-trip time of the inner ring.

The light coupled out of the ring propagates through the communication channel to the receiver. In the receiver, the signal from the transmitter, $\mathbf{E}'_R \equiv m(t)(\mathbf{E}_{T1} + \mathbf{E}_{T2})$, is split at another coupler. Ten percent of the light propagates to photodiode A where it is measured. The rest of the receiver operates on $\mathbf{E}'_R$ to mimic the dynamics of the transmitter. $\mathbf{E}'_R$ is split between the receiver's main line and outer loop. Because the relative lengths of the arms and the relative power levels in each arm have been matched to those in the transmitter, the electric field envelope when light from the two arms is recombined is $\mathbf{E}'_{R1} + \mathbf{E}'_{R2}$, where ideally $\mathbf{E}'_{R1} + \mathbf{E}'_{R2} = \mathbf{E}'_{T1} + \mathbf{E}'_{T2}$. The time delay between photodiodes A and B ensures that $m(t+\tau)(\mathbf{E}'_{T1} + \mathbf{E}'_{T2})$ is incident on photodiode A at the same time $\mathbf{E}'_{R1} + \mathbf{E}'_{R2}$ (that is $\mathbf{E}'_{T1} + \mathbf{E}'_{T2}$) is incident on photodiode B.

In the actual experiment, the lengths of the fibers forming the outer loop and main line in the receiver are matched to their counterparts in the transmitter to an accuracy of ± 3 cm. The effect of this very slight mismatch is that the relative optical phase between $\mathbf{E}'_{R1}$ and $\mathbf{E}'_{R2}$ may be different than the optical phase between $\mathbf{E}'_{T1}$ and $\mathbf{E}'_{T2}$, though the individual magnitudes are the same, $|\mathbf{E}'_{R1,2}| = |\mathbf{E}'_{T1,2}|$. Photodiode A measures the intensity

$$|m(t+\tau)(\mathbf{E}'_{T1} + \mathbf{E}'_{T2})|^2 = |m(t+\tau)|^2 \times (|\mathbf{E}'_{T1}|^2 + |\mathbf{E}'_{T2}|^2 + 2|\mathbf{E}'_{T1}||\mathbf{E}'_{T2}|\cos\theta_T\cos\varphi_T)\,, \tag{2}$$

where θ_T and φ_T represent the relative polarization and phase angles, respectively, of $\mathbf{E}'_{T1}$ and $\mathbf{E}'_{T2}$. At the same time, photodiode B measures the signal

$$|(\mathbf{E}'_{R1} + \mathbf{E}'_{R2})|^2 = (|\mathbf{E}'_{R1}|^2 + |\mathbf{E}'_{R2}|^2 + 2|\mathbf{E}'_{R1}||\mathbf{E}'_{R2}| \times \cos\theta_R\cos\varphi_R)\,. \tag{3}$$

Dividing Eq. (2) by Eq. (3) gives the message $|m(t+\tau)|^2$, but only if the interference terms, which depend on the relative polarization and phase angles, can be matched in both equations.

The coupling between the two ring lasers in the transmitter acts to maintain approximately constant values for θ_T and φ_T. Within certain constraints, the light circulating in the two ring lasers has some flexibility to adapt its wavelength and polarization to maximize the intensity of the light that passes through the modulator. The result of this optimization is an almost fixed value for $\cos\theta_T\cos\varphi_T$.

In the receiver, θ_R can be fixed to any value by the polarization controller. However, φ_R is free to fluctuate. Consequently, recovery of the message is inconsistent when $\theta_R = 0$, and this is observed experimentally. If θ_R is set to $\pi/2$, then the fluctuations in φ_R are of no consequence and the interference term at photodiode B is always zero. Obviously, errors in message recovery will result at this setting if the interference term at photodiode A is not also zero. However, we experimentally observe consistent recovery of the message even when the interference term is zero at photodiode B and not zero at photodiode A. The division used for recovery still permits accurate recovery of digital information (ones can be differentiated from zeros) because the observed behavior of $|\mathbf{E}_{T1}||\mathbf{E}_{T2}|\cos\theta_T\cos\varphi_T$ in time resembles that of $|\mathbf{E}_{T1}|^2 + |\mathbf{E}_{T2}|^2$.

Experimental results of this method are shown in Fig. 2. For this experiment, a repeating sequence of 100 000 pseudorandom bits was communicated at 126 Mbits/sec. Figure 2(A) shows 500 ns of the transmitted signal measured at photodiode A. Figure 2(B) shows the signal measured by photodiode B. Dividing the signal shown in Fig. 2(A) by the signal in Fig. 2(B) gives Fig. 2(C). The bits are clearly recovered from the chaos. Preliminary analysis of the data indicates that recovery is very consistent. The system is able to achieve bit-error rates $<10^{-5}$, except for occasional "bursting" of the transmitter (~1 ms in duration). We are investigating the origin of these intermittent bursts so that we can reduce or eliminate them in future experiments.

The recovery of the message requires that the receiver's configuration, time delays, and relative amplitudes must

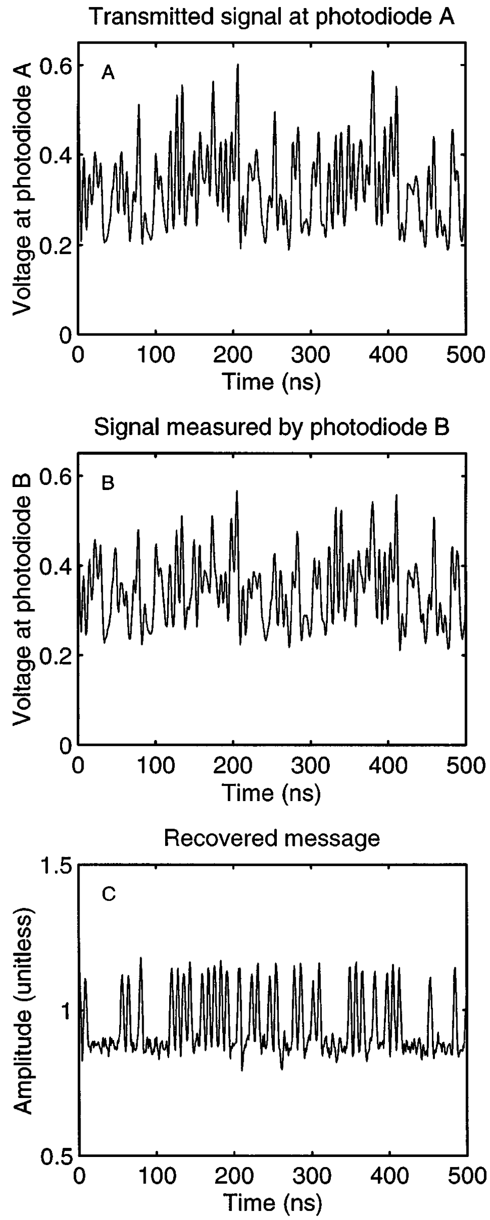

FIG. 2. (A) The transmitter output as recorded by photodiode A in the receiver. (B) Signal measured at photodiode B after passing through the matched receiver. (C) A division of (A) by (B) results in recovery of the message.

be matched to those in the transmitter. Figure 3 illustrates this point. In Fig. 3, the message is a repeating 40-bit sequence at 126 Mbits/sec. Figure 3(A) shows good recovery of the message using a properly matched receiver. Each of the other panels represents the attempted recovery of the same message using a receiver with just one parameter mismatched. Figure 3(B) shows recovery with an outer loop that is 1 m (5 ns) too long. Figure 3(C) shows the recovery of the bits when the time delay between photodiode A and photodiode B has been adjusted away from its proper value by just 1 ns. Figure 3(D) shows recovery when the amplification by EDFA 3 is inappropriately large. It indicates that the relative

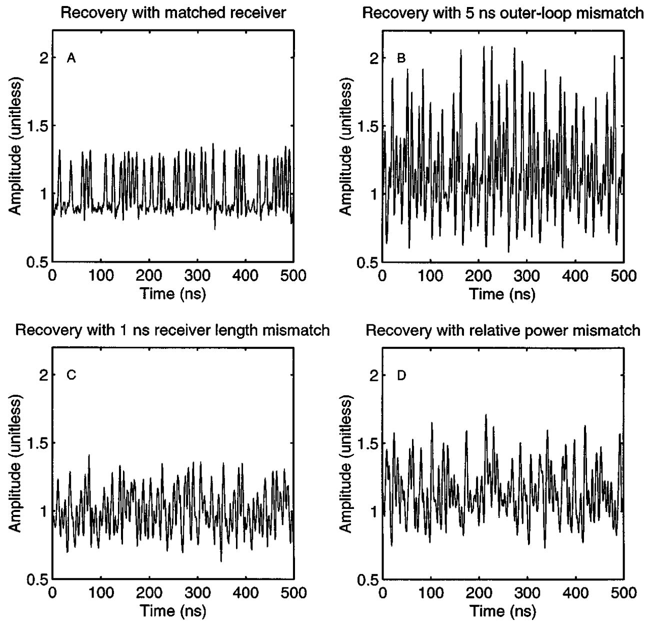

FIG. 3. (A) Message recovered by an appropriately matched receiver showing good recovery of the message, a repeating 40-bit sequence communicated at 126 Mbits/sec. (B) Message recovered with the receiver outer loop mismatched in length by 1 m ($\sim$5 ns) from the transmitter outer loop. (C) Message recovered when the time delays between photodiode *A* and photodiode *B* are mismatched by 1 ns ($\sim$20 cm of fiber). (D) Message recovery when the relative amplitude of $\mathbf{E}'_{R2}$ compared to $\mathbf{E}'_{R1}$ in inappropriately large. All of these panels demonstrate the fact that the receiver must be appropriately matched to the transmitter for accurate message reception.

amplitudes of $\mathbf{E}_{R1}$ and $\mathbf{E}_{R2}$ must be properly adjusted in order to recover the message. For the data shown in Fig. 3(D), the pump power in EDFA 3 was raised from 22 mW (optimum message recovery) to 79 mW; pump powers up to 150 mW are possible.

The transmitter parameters that must be known in order to recover the message form a multidimensional space in which to hide the "key" for recovery. Conceptually, it seems possible to construct even more geometrically complicated transmitters (and thus receivers) so that the parameter space can become even higher dimensional.

We thank Henry Abarbanel, Matt Kennel, Steve Strogatz, and all others (at UCSD, Cornell, and Georgia Tech) involved in our collaboration, through National Science Foundation Grant No. NCR961225, for helpful discussions. We gratefully acknowledge support from the Office of Naval Research, and thank C. Verber, P. Juodawlkis, and M. Gross for providing essential instrumentation and encouragement.

*Email address: rajarshi.roy@physics.gatech.edu

[1] L. M. Pecora and T. L. Carroll, Phys. Rev. A **44**, 2374 (1991); K. M. Cuomo and A. V. Oppenheim, Phys. Rev. Lett. **71**, 65 (1993); S. Hayes, C. Grebogi, E. Ott, and A. Mark, Phys. Rev. Lett. **73**, 1781 (1994).

[2] L. Kocarev, K. S. Halle, K. Eckert, L. O. Chua, and U. Parlitz, Int. J. Bifurcation Chaos Appl. Sci. Eng. **2**, 709 (1992); U. Parlitz, L. Kocarev, T. Stojanovski, and H. Preckel, Phys. Rev. E **53**, 4351 (1996); A. R. Volkovskii and N. Rulkov, Tech. Phys. Lett. **19**, 97 (1993).

[3] K. M. Short, Int. J. Bifurcation Chaos Appl. Sci. Eng. **6**, 367 (1996); **4**, 959 (1994); G. Perez and H. A. Cerdeira, Phys. Rev. Lett. **74**, 1970 (1995).

[4] J. Goedgebuer, L. Larger, and H. Porte, Phys. Rev. Lett. **80**, 2249 (1998).

[5] G. D. VanWiggeren and R. Roy, Science **279**, 1198 (1998).

[6] H. D. I. Abarbanel and M. B. Kennel, Phys. Rev. Lett. **80**, 3153 (1998); Q. L. Williams, J. Garcia-Ojalvo, and R. Roy, Phys. Rev. A **55**, 2376 (1997).

[7] H. D. I. Abarbanel, *Analysis of Observed Chaotic Data* (Springer-Verlag, New York, 1996).