High-precision ranging using a chaotic laser pulse train

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(Received 9 November 2000; accepted for publication 22 January 2001)

We demonstrate the use of a chaotic laser pulse train for high-precision ranging. The pulse train is produced by inducing coherence collapse in an AlGaAs semiconductor laser. Measurements of optical spectra, intensity autocorrelation functions, and ladar ranging are presented. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1355663]

Semiconductor lasers subjected to moderate levels of optical feedback from an external reflector exhibit severe spectral broadening, a phenomenon referred to as *coherence collapse*.[1] While the average output power of the system remains the same as the case without feedback, the optical power is distributed over a spectral width of about 50 GHz for feedback levels on the order of 10%. This is in contrast to the typical 10 MHz order of magnitude linewidth of a solitary diode laser.[2] Severe spectral broadening of the laser output, when considered in the time domain, results from the emission of an aperiodic train of short pulses ≈ 50 ps full width at half maximum (FWHM) at an average repetition rate >3 GHz.[3] The pulse train is *chaotic*, arising from the well-known deterministic dynamics of the semiconductor laser with optical feedback described by the Lang–Kobayashi (LK) equations.[4,5] While previous research has focused on the suppression of coherence collapse,[6,7] this letter proposes and demonstrates a useful application of the chaotic laser pulse train arising from coherence collapse. The output wave form is well suited for what has been called *noise radar* or *correlation radar*.[8] The chaotic laser can serve as a signal source for radar or it may be used directly in the optical regime for *correlation ladar*. In correlation radar/ladar, a random or pseudorandom wave form is reflected from a target and correlated against a delayed reference wave form from the same source. The delay time in the reference channel required to observe a peak in the correlation signal is the round-trip time of the reflected signal. The chaotic pulse train from a semiconductor laser operating in the coherence collapse regime has several desirable properties for ladar and radar applications: (1) short pulse width, which provides the bandwidth for high-precision range measurements; (2) rapid decorrelation due to irregular pulse intervals and amplitudes, which yields unambiguous range measurements; and (3) a high average pulse repetition frequency (PRF), which provides a significant integration gain in the signal-to-noise ratio for the system. Furthermore, this wave form permits the system to be operated in cw—i.e., pulse forming electronics are not required. In this letter we present experimental results for a ladar system demonstrating range measurement with millimeter precision.

A block diagram of the laboratory experimental arrangement is given in Fig. 1. The collimated output of a temperature stabilized AlGaAs diode laser (Sharp LT015MD, $\lambda = 830$ nm) is directed to a variable external reflector R with fine two-axis tilt adjustments. By changing the tilts, the amplitude and phase of the feedback can be adjusted to place the laser in the coherence collapsed state. The external reflector R is placed at a distance of 22 cm from the diode laser. Behind the external reflector, a beamsplitter BS1 reflects a portion of the laser output through a 38 dB optical isolator ISO1, into a focusing lens L1, and onto a 25 GHz bandwidth InGaAs detector D1. The output of D1 is transmitted through a variable delay line DL1 to provide the reference input for a high-speed analog correlator. The transmitted beam from BS1 passes through a 40 dB isolator ISO2 and onto a second beamsplitter BS2. The reflected beam from BS2 is directed into a second lens and detector D2. The delay line DL1 is a ''trombone,'' consisting of a pair of concentric (air gap) coaxial lines which can be slid into or out of each other, thereby providing a variable length coaxial cable. The tuning range for DL1 is approximately 1 ns. The high-speed correlator consists of a series of amplification stages for both the reference and signal inputs, followed by a wide band mixer (Mini-Circuits ZEM-M2TMH), an amplifier at the output of the mixer, a diode detector, and a standard voltmeter. The bandwidth of the combined components, excluding the voltmeter, is 3.6 GHz. The voltmeter, with a bandwidth of a few hertz, serves as a crude pulse integrator owing to its input low-pass filter.

The transmitted beam from BS2 passes through another isolator ISO3 and into a scanning Fabry–Pérot interferometer. The interferometer, with a finesse of 170 and a free spectral range (FSR) of 330 GHz, permits continuous obser-

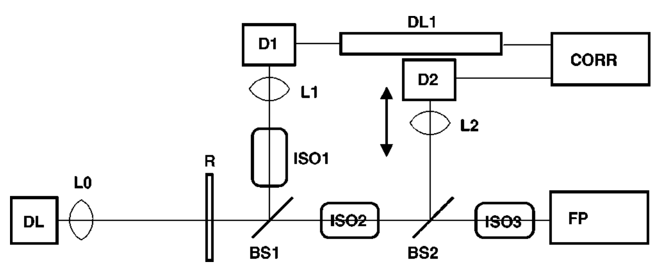

FIG. 1. Experimental system for observing the spectra and autocorrelation functions of a chaotic diode laser.

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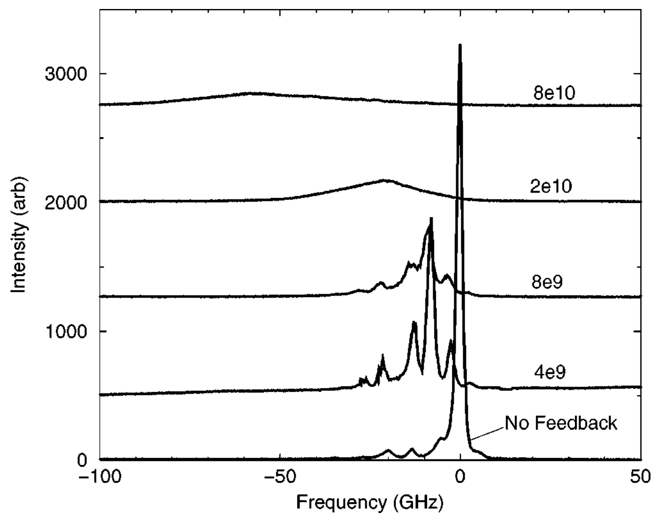

FIG. 2. Spectra of the Sharp LT015MD diode laser output with the following feedback rates: $\gamma=0$, $4\times10^{9}\,s^{-1}$, $8\times10^{9}\,s^{-1}$, $2\times10^{10}\,s^{-1}$, and $8\times10^{10}\,s^{-1}$.

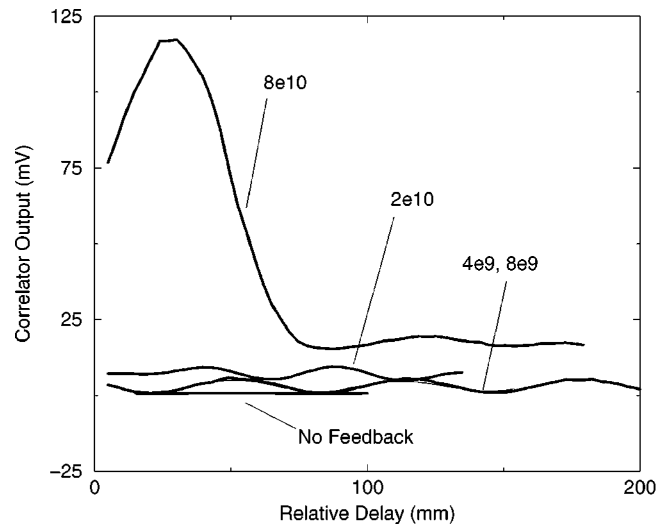

FIG. 3. Autocorrelation functions of the laser output for the same values of γ as in Fig. 2.

vation of the spectrum of the diode laser. The large FSR allows a study of the unfolded laser spectrum even under the severe broadening produced by the feedback. The shape of the spectrum is found to depend sensitively on the amount of optical feedback injected into the laser. Thus, the Fabry–Pérot interferometer not only allows for monitoring of the spectrum, but enables the feedback to be adjusted in a reproducible manner.

Figure 2 shows spectra of the laser with varying amounts of optical feedback. Direct quantitative measurements of the feedback strength were not possible with our measurement system, since the feedback coupling efficiency into the laser cannot be easily determined. Instead, we estimated the feedback strength by comparing the observed spectra with those computed from the LK equations using measured and estimated parameters for our laser. Another technique of estimating feedback strength is to measure the lowering of threshold current with feedback.[9] However, the accuracy of both techniques is limited by the accuracy to which the laser parameters are known, since the LK equations are used in both cases to model the experiment. We expect the spectral technique to provide better sensitivity at low feedback rates. Simulated spectra are obtained by measurement with a fast Fourier transform spectrum analyzer of the output of an analog computer designed to solve the LK equations. The LK simulator will be discussed elsewhere; however, it is sufficient for our purposes to note that the simulated time-averaged spectra reproduced the qualitative appearance and the quantitative spectral widths of the observed spectra as the feedback rate was varied. Estimates of the feedback rates γ (using the notation of Ref. 1) for the corresponding spectra are given in Fig. 2. We believe the estimates for γ are valid to within a factor of 2. For the case of greatest spectral width, 50 GHz FWHM, we find $\gamma\approx8\times10^{10}\,s^{-1}$.

The autocorrelation function of the laser intensity was observed by splitting the output of the first detector D1 into two signals using a rf splitter and feeding the two identical outputs to the reference and signal inputs of the correlator. For the set of feedback rates giving rise to the spectra in Fig. 2, the corresponding autocorrelation function was mapped by varying the delay DL1 and recording the output of the correlator at each delay. The autocorrelation functions are shown in Fig. 3. Note that the no feedback case shows a flat, nearly zero autocorrelation output. This is a result of the fact that the intensity output of the laser is essentially constant in time, while the input amplifiers to the correlator are ac coupled. Upon close examination of these data, a very weak fluctuation with a period of 210 ps is seen in the autocorrelation function. This frequency component is due to the presence of damped relaxation oscillations, excited by phase and amplitude noise, in the solitary laser output.[2] The frequency component can be seen as weak sidebands at ±5 GHz to the central line of the solitary laser spectrum in Fig. 2. With $\gamma\approx2\times10^{10}\,s^{-1}$, the sinusoidal modulation of the autocorrelation function is greatly enhanced, and the overall dc level of the correlator output is increased. The rise in the dc level of the correlator output is an indication of larger amplitude temporal fluctuations in the detector signal. At $\gamma\approx8\times10^{10}\,s^{-1}$, we observe a dramatic change in the output of the correlator: the autocorrelation function shows a pronounced peak. The peak and the correspondingly broad spectrum obtained at this γ indicate the emission of a fast irregular pulse train from the diode laser. It is in this regime that the output signal is useful for the laser ranging experiment described below.

Laboratory demonstration of range measurement using the chaotic laser output was performed using the outputs of detectors D1 and D2. Referring to Fig. 1, D1 provides the reference input for the correlator while D2 provides the signal input. In a monostatic ladar configuration, D1 and D2 are situated close to each other, and the optical path of the beam from BS1 to D2 includes the round-trip path to the target. In this experiment we chose to demonstrate a change in the range to the target by simply translating detector D2 by a known amount. The output of the correlator, as a function of the adjustable delay, is shown in Fig. 4 for the two positions of D2. The peak in the correlation signal is seen to shift by an amount of 17.4 ± 2 mm. This distance represents the change in range of the target, and is in agreement with the independently measured change in the D2 position of 18.5 mm.

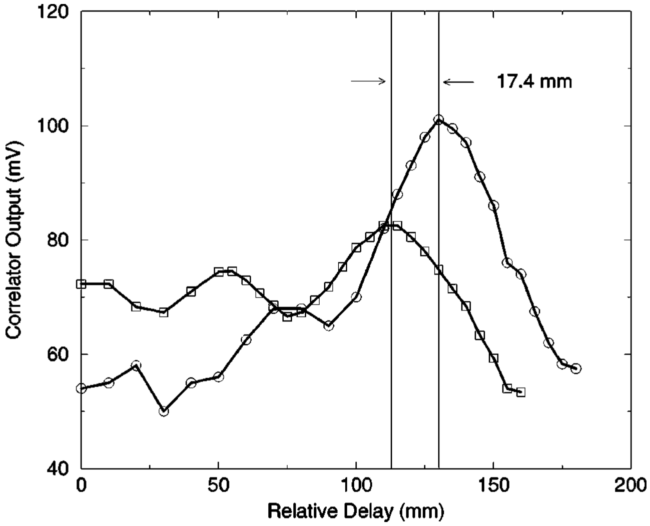

FIG. 4. Delta range measurement using the chaotic laser. The shift in the peak of the autocorrelation function corresponds to the change in range to the target.

In conclusion, we have demonstrated use of the chaotic output of a semiconductor laser for range determination. The high bandwidth and rapid decorrelation of the laser pulse train, produced when the laser is placed into a state of severe coherence collapse, provides an unambiguous autocorrelation signal for measuring round-trip time delay. Compared with commercial ladar systems which use the time-of-flight measurement technique to achieve 10 mm resolution, typically, we have already demonstrated millimeter resolution and accuracy with the chaos ladar technique. Improvements in the signal-to-noise ratio (SNR) of the correlator, achievable with the use of higher bandwidth components and a more efficient pulse integrator, should permit submillimeter accuracy. While the 4 GHz bandwidth of the correlation electronics used in this experiment may seem incongruous with an optical spectral width of tens of GHz, it is noted that the *intensity spectrum* has a peak at the relaxation oscillation frequency. Thus, increasing the bandwidth of the correlator to >5 GHz should provide a significant improvement in the SNR. Although a rapid method of switching/scanning the delay in the reference channel is needed to enable practical utilization of this concept in tracking ladar or radar, the technique can be readily utilized for fixed range detection applications such as collision avoidance systems.

The authors wish to acknowledge the assistance of Terry A. Okonek with the laboratory setup for this experiment. Three of the authors (K.M., T.A.B., and B.R.R.) were supported for this work by the Defense Advanced Research Projects Agency, Contract No. DAAH01-98-C-R093.

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