Self-organized learning of purely temporal information in a photorefractive optical resonator

Germano Montemezzani, Gan Zhou, and Dana Z. Anderson

Department of Physics and Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder, Colorado 80309-0440

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A photorefractive resonator containing an optical delay line is shown to learn temporal information through a self-organization process. We present experiments in which a resonator mode selectively learns the most-frequently presented signals at the input. We also demonstrate the self-organized association of two different analog signals with two different resonator modes.

Tune across a short-wave radio band and it is easy to recognize a channel that carries Morse code, even if you do not know the code. That is because Morse code consists of a simple set of temporal features (a dot, a dash, and two pause lengths) and a Morse signal is characterized by repeated occurrences of these features. It does not take long for the brain to identify these features as the dominant content of the received signal. In this Letter we present a photorefractive optical system whose task is just this: to discover, on its own, the dominant features in a temporal signal characterized by repetitive entities. This task is a precursor of the more complex processing required for the self-organized feature extraction and recognition of audio and sonar signals.

In many studies, photorefractive gratings have been used to store and classify purely spatial information carried by optical beams.\(^1\) With the addition of temporary optical storage provided by a photorefractive delay line,\(^3\) photorefractive gratings have also been programmed to classify temporal structures such as spoken words that were learned in a supervised fashion.\(^4\) In this case supervised means that there is a programming stage in which the knowledge of a teacher provides essential information. Here we show that by placing a delay line in the feedback path of a photorefractive ring oscillator we can have the system learn certain kinds of repetitive features in a self-organized way.

A conceptual schematic illustrating the principles of our system is shown in Fig. 1. Each ring in the figure corresponds to a spatial mode in the optical resonator. The group of modes shares a photorefractive gain crystal and is arranged along the delay coordinates of an optical delay line. The delay line temporarily stores the optical field of each mode (e.g., mode \(j\)), and later injects the stored field into the neighbor mode (\(j+1\)). Its action can be expressed as

\[
E_{j+1}(t) = G_{j+1}S(t + k\tau) + \mu E_j(t - \tau) \quad (j = 1, \ldots, n - 1),
\]

where \(E_j(t)\) is the optical field within mode \(j\) at time \(t\), \(G_j\) is a normalized grating component in the gain crystal, and \(0 < \mu < 1\) is a numerical factor characterizing the decay along the delay line. The temporal signal \(S(t)\) is imposed on a pump beam as modulation on its amplitude and/or phase; this serves as input to the system. The grating \(G_j\) in the gain crystal scatters the pump beam into the \(j\)th resonator mode; this part of the light contains information about the present input. In addition, each mode receives injected light from the delay line containing information about past input signals. For clarity of presentation we assumed a spatially discrete array of \(n\) modes with time delay \(\tau\) between two neighboring modes. However, the modes can also be continuous, as in the experiments described below. Using Eq. (1), we can write the total optical field \(E_j(t)\) in the \(j\)th mode at time \(t\) as

\[
E_j(t) = \sum_{k=1}^{n} G_kS(t - j\tau + k\tau) + \mu E_j(t - \tau) \quad (j = 1, \ldots, n).
\]

Thus, given a set of gratings, the optical field in a mode is an inner product of the gratings and the input signal. The gratings can be thought of as defining a learned basis set of temporal features corresponding to the signal.

The photorefractive grating in the gain crystal starts from noise and grows when oscillations in the resonator begin to build up. The growth process is governed by photorefractive dynamics and can be qualitatively understood as follows: In general, the equilibrium state of the grating is determined by the input temporal signals. Suppose that two temporally orthogonal signals (zero-overlap integral in

![Fig. 1. Schematic of an optical resonator incorporating a delay line for learning temporal information.](https://example.com/schematic.png)
time) $S_1$ and $S_2$ are presented alternately. Each signal tries to establish a set of gratings that corresponds to its own temporal characteristics. Competition between the two signals results from a loss imposed by the gratings of one signal on the oscillating beam of the other. It is energetically unfavorable to have both sets of gratings present in the gain crystal. If the input is biased such that one of the signals is presented with a higher probability, then its set of gratings will have an advantage, and the growth of the second set of gratings will be suppressed in a way qualitatively similar to mode competition in lasers. In this case, the system has learned to pick out the most-frequently-presented signal. Note that in Fig. 1 we showed only one group of modes. We refer to such a group of coupled modes as a chronomode. In principle, the system in Fig. 1 can have multiple chronomodes arranged along different delay lines, and each of them can learn a particular temporal signal.

The experimental implementation is shown in Fig. 2, in which all the optical beams are from a single-frequency cw Ar-ion laser ($\lambda = 514$ nm) and are $p$ polarized. The system consists of a resonator formed between the photorefractive delay line (rotating crystal BaTiO$_3$ #1) (Ref. 3) and feedback mirror $M_1$. The resonator is pumped by a modulated Gaussian beam entering the gain crystal (45°-cut BaTiO$_3$ #3) that lies in the image plane of crystal #1. The delay line works in the phase-conjugate configuration, and the counterpropagating pump beam arises by four-wave mixing in a third crystal (BaTiO$_3$ #2). Each mode in the resonator finishes a round trip by tracing the same path twice and reflecting twice at crystal #1. The optical phase is reproduced after one round trip, and resonance condition is maintained independently of the optical path length. The time-delay coordinate of the delay line is along a cone, and a short portion of it essentially lies along the direction perpendicular to the plane of Fig. 2. A group of modes distributed along this vertical direction defines a chronomode. The transverse profile of a single chronomode is constrained by a pair of slot apertures in the horizontal plane. One can define multiple chronomodes by placing more aperture pairs in the system, as shown in Fig. 2 (where two chronomodes are shown). This is done without addition of more crystals to the system as long as there is sufficient gain in the pump crystal (#3), so that all chronomodes can be above threshold and can oscillate. The vertical lengths of the slot apertures define the angular range over which modes enter the delay line and gain crystals, which effectively defines the maximum usable time delay, i.e., the maximum feature length that can be detected.

In the first experiment we demonstrate competitive learning of the most-frequently presented input signal. We block a pair of aperture slots and permit only one chronomode. The input wave is phase modulated by a ferroelectric liquid-crystal cell (response time 200 $\mu$s) in a binary way—the optical phase is switched by 180° with no intensity modulation. We choose two different binary signals, each consisting of 16 bits with 10-ms bit length. The first signal is $S_1 = (+ - - - - - - + + + + + + + +)$, where + and − indicate optical beams with opposite phase. The second signal is $S_2 = (+ + + + + + + + + + + + + +)$. The two signals are alternated at the input with a 300-ms dark time (provided by a shutter) between two successive presentations. During learning we deliberately bias the input such that one of the signals is presented twice as often as the other. In the experiment, the delay line crystal (#1) rotates at 1.5 rpm, giving an estimated bandwidth of approximately 140 Hz. This gives the limiting time resolution of the system. Larger bandwidths can be obtained by faster rotation of the crystal; however, this reduces the delay line reflectivity and thus requires a higher-gain threshold for oscillation. The maximum delay time allowed by the aperture is 200 ms and is shorter than the grating decay time in the rotating crystal. Thus features as long as 200 ms can be detected. The small-signal intensity gain is 3000 for the beam that enters the gain crystal from the same side as the pump beam; it is 100 for the beam that enters from the opposite side.

After approximately 20 learning cycles, the resonator settles into an equilibrium state. The response at this state is shown in Fig. 3, in which the total intensity of the resonator as a function of time is plotted as different signals are applied at the input. The two plots correspond to the result of different choices of the most-frequently-presented signal. The upward square pulse shown on the lower part of each plot indicates the time at which signal $S_1$ is applied; the downward pulse is a label for $S_2$. Clearly the intensity is much larger when the more-often-presented signal is at the input. The average contrast ratio between the response to the two signals is approximately 10:1. An interesting feature of the self-organized state is that, as a learned signal is presented, the resonator response grows continually from the beginning to the end. The system can be thought of as being able to accumulate evidence continually over time. In a sense this is similar to our ability to anticipate and make predictions continually, e.g., as we listen to music. Such a property was not present in the previously implemented supervised processor for temporal optical signals.
Fig. 3. Steady-state resonator response after presentation of two binary sequences $S_1$ and $S_2$ (see text for definitions): (a) $S_1$ presented twice as often and learned, (b) $S_2$ presented twice as often and learned. The lower trace indicates which input signal is on at a given time. Note that the system response grows from the beginning until the end of a signal, then it decays.

Fig. 4. Association of two partially noisy time signals with two chronomodes. (a) Time-dependent amplitude of the two input signals presented alternately, (b) instantaneous intensity profile of the two modes after Signal 1 has just been applied, (c) same intensity profile with Signal 2 at the input. In each picture the lower chronomode is associated with Signal 1 and the upper with Signal 2. Images are taken by a CCD camera at the place of the detector in Fig. 2.

Next we demonstrate the separation of two different analog signals into two different resonator chronomodes. Both pairs of apertures are now open. Here the input signals are generated by an electro-optic modulator. The forms of the two phase-modulated wave amplitudes are shown in Fig. 4(a).

They consist of underlying sinusoidal waveforms $S(t) = E_0 \sin(2\pi \nu_m t)$, with frequency $\nu_m = 19.3$ Hz (Signal 1) or 33.9 Hz (Signal 2), and noiselike components added to them. The random noise components have a maximum amplitude that is twice the amplitude $E_0$ of the sinusoidal waveforms; their maximum bandwidth is approximately 100 Hz. They are different for Signals 1 and 2, but they do not change between successive presentations. The two signals are presented equally often during learning. Figures 4(b) and 4(c) show the responses of the two modes when the resonator has settled down to a self-organized state (after 20–30 cycles of presentation). Each image corresponds to the resonator intensity profile when one of the signals is applied. Note that in reality the mode intensity profile changes with time. The position of maximum intensity shifts from left to right in the figure because of the action of the delay line. One sees that one of the chronomodes responds strongly to Signal 1 and the other to Signal 2. Each chronomode has learned to associate with a particular signal. The particular kind of association cannot be predicted, and different experiments may lead to reversed results, because the whole process starts from noise. The results shown here are somewhat similar to the function of the photorefractive frequency demultiplexer, except that the input optical signals here have the same spatial profile. Note that in this experiment the basis for the recognition is given by the highly autocorrelated sinusoidal functions that underlie the two signals. Completely noisy and unstructured signals cannot be learned by our system.

The optical system presented here also could, in principle, handle spatial information by using a spatial light modulator for the input beam. The learning of sequences of images is closely related to the problem of speech recognition and is the subject of ongoing investigations.

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References