

# Sluggish light for radio-frequency true-time-delay applications with a large time–bandwidth product

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Received June 7, 2006; revised September 4, 2006; accepted September 7, 2006;  
posted September 11, 2006 (Doc. ID 71662); published October 26, 2006

A new radio-frequency (RF) photonic technique for achieving large RF time delays has been experimentally demonstrated using femtosecond pulses modulated by an acousto-optic tunable filter in a frequency-mapped and Doppler-shifted modulation scheme. A short optical delay line with length of 240  $\mu\text{m}$  produces nearly 3  $\mu\text{s}$  RF time delay after optical heterodyne detection, resulting in an effective slow-light velocity of 86 m/s. A delay-to-pulse-width ratio of 20 based on this technique has been observed, with a larger fractional delay foreseeable. © 2006 Optical Society of America  
OCIS codes: 320.7120, 280.4750, 280.5110, 070.1060.

Recently there has been great interest in slowing light through various mechanisms, such as electromagnetically induced transparency,<sup>1</sup> and in photonic crystals<sup>2</sup> or coupled resonators.<sup>3</sup> Through these processes, a sharp resonance is induced in the engineered materials and the group index  $n_g$  can be increased by orders of magnitude near that resonance, leading to the slow-light effect.

Potential applications using slow light include data buffering and synchronization in optical communication networks<sup>4</sup> and radio-frequency (RF) photonic signal processors, such as true-time-delay (TTD) beam-forming systems for wideband RF phased-array antennas.<sup>5</sup> In these applications, the amount of optical delay required usually should be many times longer than the bandwidth-limited duration of the delayed optical pulses. This time–bandwidth product (TBP) of the delayed optical pulses describes the number of degrees of freedom stored in the optical delay lines and determines the maximum size of the array and corresponding number of RF antenna elements that can be processed in wideband RF photonic TTD beamformers. However, in conventional slow-light mechanisms the TBP is fundamentally restricted by an intrinsic trade-off between the steepness of the dispersion curve and the resonance width, as well as by absorption and four-wave mixing.<sup>6–8</sup> A recent attempt to increase the TBP of slow light used probing light between two absorption resonances<sup>9</sup> to increase the TBP to over 10, still far below the requirements for RF TTD beam steering.

In this Letter, we introduce a novel slow-light like effect based on frequency-mapped, Doppler-shifted modulation and heterodyne detection using an acousto-optic tunable filter (AOTF) and a femtosecond pulse train. We call it “sluggish” light to indicate its similar operation but distinct mechanism compared with conventional slow light and as an acronym for “slow-light using ultrasonic-grating-generated interferometric spectral heterodyne.” Each frequency component of the RF waveform applied to the AOTF launches a traveling-wave periodic dielectric perturbation that diffracts about 1 nm wide opti-

cal bandpass of a wideband illuminating femtosecond comb with a center frequency proportional to the RF frequency. The diffracted light is simultaneously polarization switched and Doppler shifted by the applied RF tone. This produces pulse-compressed optical waveforms from each femtosecond pulse, and the heterodyne detection of the modulated comb with the comb reference reproduces the applied RF signal with a magnified delay determined by the micrometer scale path length difference between the two arms. This is fundamentally different from conventional acousto-optic deflector-based RF photonic delay lines<sup>10</sup> where different Doppler channels are angularly separated by a Bragg cell and from the channelization slow-light scheme<sup>11</sup> where different optical frequencies are angularly dispersed by prisms. These schemes require an additional spatial dimension for manipulating different optical frequencies by applying appropriate linear phase factors with a prism or tilted mirror, and these are not suitable for beam forming of two-dimensional (2D) RF phased-array antennas that have already used up all the available spatial dimensions.

Based on the sluggish-light effect, a novel TTD Fourier lens multiple beam-forming system for 2D wideband RF phased-array antennas has been developed.<sup>12</sup> Conventional Fourier-lens beam formers can only process signals from narrowband RF antenna arrays without suffering from unwanted beam squint.<sup>5</sup> This is because the time delay required to compensate for the effects of RF propagation across the array scales with the array size (many meters to kilometers), while the compensation time delay available in a conventional lens is limited by the millimeter thicknesses. However, when an optical lens is used in conjunction with the sluggish-light effect, each AOTF-modulated optical beam carrying RF signals from different antenna elements passes through different portions of the lens. Although the path length difference is much smaller than the RF phased-array aperture, the magnified time delay for the heterodyne-detected RF signal is of the same order as the necessary TTD compensation for squint-free beam forming.

Unlike conventional RF photonic TTD techniques, where a CW laser is used as the information carrier modulated by either an electro-optic modulator or an acousto-optic modulator, in the sluggish-light-based delay lines we use a broadband light source, such as a femtosecond pulse train, modulated by an AOTF in a frequency-mapped manner.<sup>13</sup> Only the phase-matched optical frequency components polarized as one eigenmode of the crystal will be diffracted into the orthogonal eigenmode by the acoustic grating excited by the corresponding frequency components of the applied RF signal. The simplified phase-matching condition for a collinear AOTF can be rewritten as a frequency-mapping relationship,  $\alpha^{-1} = (\Omega/\omega) \approx |n_e(\omega) - n_o(\omega)|(V_a/c)$ , where  $\omega$  and  $\Omega$  are the optical and the RF angular frequency, respectively;  $n_e(\omega)$  and  $n_o(\omega)$  are the extraordinary and ordinary refractive index of the crystal, respectively;  $V_a$  is the acoustic velocity; and  $c$  is the speed of light. Therefore, a frequency-mapping relationship can be established between the RF and optical frequency components, and the mapping factor  $\alpha$  is typically about  $10^6$  in an AOTF. Because the electric field of the diffracted optical components is proportional to the amplitude of the mapped RF components with the RF phases preserved, we can use the AOTF as a frequency-mapped modulator that can modulate a wideband RF signal onto a broadband optical carrier with the same fractional bandwidth. Due to the moving nature of the acoustic grating, the diffracted optical frequency components are Doppler shifted by the corresponding RF tone.

We use Fig. 1 to illustrate the AOTF modulation process when three RF tones at 90, 100, and 110 MHz are applied to the AOTF and a femtosecond comb is used to read out the acoustic gratings. Using the frequency-mapping factor  $\alpha = 4 \times 10^6$ , three spectral bands of the optical comb lines near 360, 400, and 440 THz are diffracted and Doppler shifted by the three RF tones, respectively. The number of the comb lines within each diffracted group is determined by the resolution of the AOTF and the repetition rate of the laser. The dashed lines in Fig. 1(b) are undiffracted reference comb lines, and the solid lines are the diffracted and Doppler-shifted comb orders. For RF signal recovery, heterodyne detection between the diffracted comb and the undiffracted reference comb reproduces the RF tones at 90, 100, and 110 MHz. Higher-order RF components separated by the repetition rate of the femtosecond laser may also exist due to the beating between the modulated comb lines with adjacent reference comb lines. A photo-

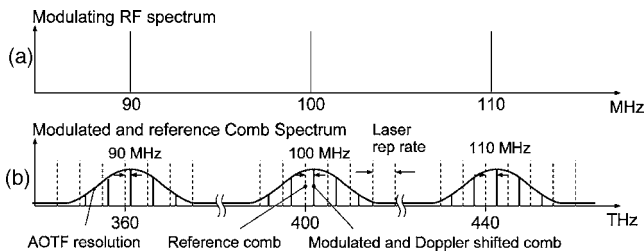


Fig. 1. Femtosecond comb modulated by 3 RF tones using an AOTF with frequency-dependent Doppler shift.

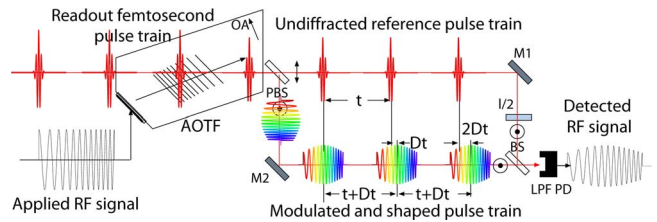


Fig. 2. (Color online) Time domain interpretation of the readout of an AOTF with a femtosecond comb and subsequent heterodyne detection to reproduce the applied RF signal.

diode that does not respond to the higher frequencies can be used to remove all the unwanted aliased orders.

When a wideband RF signal, such as a chirped pulse, is applied to the AOTF and a femtosecond pulse train with the same fractional bandwidth is used to read out the grating, the entire optical spectrum of the readout pulse train will be diffracted into the orthogonal polarization. The diffracted optical pulse is a compressed-by- $\alpha$  temporal image of the modulating RF signal convolved with the envelope of the femtosecond pulse, as shown in Fig. 2. This is similar to the pulse-shaping operation in an acousto-optic programmable dispersive filter (AOPDF),<sup>14</sup> except that the AOPDF pulse shaping is limited to a kilohertz repetition rate of the laser pulses from a regenerate amplifier due to the required synchronization between the femtosecond pulse with the RF and corresponding acoustic wave in the device aperture. In the frequency-mapped modulation, no synchronization is necessary since the acoustic wave slowly drifts as it is sampled by a much faster propagating sequence of laser pulses, as long as the repetition rate adequately samples the RF bandwidth. The period of the shaped pulse train is changed by  $\Delta\tau = \tau|n_e - n_o|(V_a/c)$  due to the acoustic wave drift from pulse to pulse and the birefringence as shown in Fig. 2, where  $\tau$  is the period of the reference pulse train. The compression between the RF signal and the modulated optical pulses can be considered as an analogy of the compression in conventional slow-light experiments where light pulses are compressed in the slow-light medium by the enlarged group velocity. When the compressed optical pulse train propagates through an optical delay line and is then heterodyne detected with the reference pulse train, a time delay magnified by  $\alpha$  is achieved for the detected RF signal.

A brief analysis of the sluggish-light effect is given here in the frequency domain. When an optical free-space delay line with length  $L$  is inserted in the modulated arm in the heterodyne system shown in Fig. 2, a linearly varying spectral phase change of  $\phi(\omega) = \omega L/c$  is induced. In conventional RF or RF photonic delay lines, such a linear phase ramp results in a time delay  $T_d = d\phi(\omega)/d\omega = L/c$ . However, in the sluggish-light scheme, this spectral phase change is mapped and impressed onto the spectrum of the heterodyne-detected RF signal. Due to the frequency conversion between the optical and RF, the time delay of the detected RF signal, assuming a linear

frequency-mapping relationship with a constant mapping factor  $\alpha$ , is determined by

$$T_d = \frac{d\phi(\omega)}{d\Omega} = \frac{d(\omega L/c)}{d(\omega/\alpha)} = \frac{L}{c/\alpha} \equiv \frac{L}{v_s}, \quad (1)$$

where  $v_s = c/\alpha$  is the effective slow-light velocity.

In the experiments, a conventional  $\text{TeO}_2$ -based AOTF is used that has an RF bandwidth from 70 to 140 MHz that covers an octave optical tuning range from 500 to 1000 nm. An ultracompact ring-cavity Ti:sapphire laser with a 2 GHz repetition rate and 60 nm bandwidth at a center wavelength of 800 nm is used as the broadband optical carrier, limiting the fractional bandwidth of the modulation to 60/800. The experimental setup is shown in Fig. 3. An RF sinc pulse with 6.5 MHz bandwidth at center frequency of 90 MHz (frequency mapped to 800 nm) is applied to the AOTF and produces a polarization-switched and Doppler-shifted diffraction. The undiffracted beam refracts at a different angle than the diffracted beam at the exit face of the crystal and is used as the heterodyne reference, since upon propagation through the  $\text{TeO}_2$  crystal it acquires nearly the same dispersion as the diffracted pulses. Heterodyne detection reproduces the RF signal with a time delay that can be varied by adding slight optical delays in the diffracted arm. Figure 4 shows the experimental results of the RF time delays versus the optical delay. The detected RF pulse with a pulse width of 150 ns was delayed by about 3  $\mu\text{s}$  when the optical delay was varied by 240  $\mu\text{m}$ , leading to a fractional time delay of 3  $\mu\text{s}/150 \text{ ns} = 20$  and an effective slow-light velocity of  $v_s = 86.5 \text{ m/s}$ .

In this Letter, we experimentally demonstrate a novel RF photonic time-delay technique based on the sluggish-light effect. In the proof-of-concept experiments, a femtosecond laser is used with a conventional AOTF, limiting the modulation bandwidth to 6.5 MHz and the TBP of the sluggish light to 20. An octave-spanning supercontinuum or even a white-light source can be used to further increase the TBP to about 200 with the same AOTF or to nearly 1000

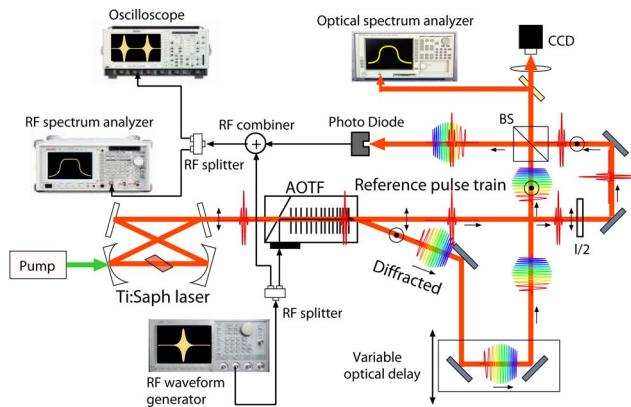


Fig. 3. (Color online) Experimental setup for sluggish light. The modulated pulse train is delayed with respect to the undiffracted pulse train (the reference), resulting in a magnified time delay for the heterodyne-detected RF signal. DPSS pump, diode-pumped solid-state pump; BS, beam splitter.

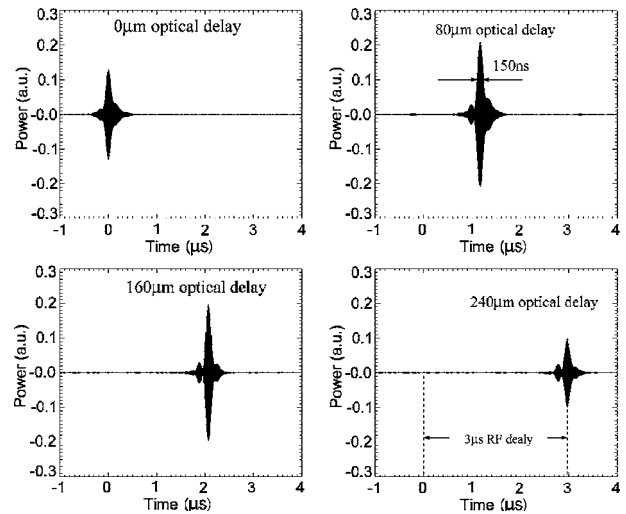


Fig. 4. Sluggish-light experimental results of a 150 ns RF signal delayed by 3  $\mu\text{s}$  via an optical free-space delay of 240  $\mu\text{m}$ , achieving a time-bandwidth product of 20.

with a higher-resolution AOTF. For practical RF photonic signal processing applications, multi-GHz or higher RF bandwidth is required. This can be achieved by employing a reflection-based AOTF for multi-GHz bandwidth or a traveling-wave electro-optic tunable filter<sup>13</sup> for 20 GHz or higher bandwidth. This sluggish-light effect can be used in conjunction with a conventional optical lens to build a novel TTD beam-forming system for squint-free, multiple beam steering of 2D wideband RF phased-array antennas.

This work was supported by the National Reconnaissance Office Director's Innovation Initiate program. L. Gao's e-mail address is lu.gao@colorado.edu.

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