A slow-light laser radar system with two-dimensional scanning

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We propose a multi-aperture slow-light laser radar with two-dimensional scanning. We demonstrate experimentally that we can use two independent slow-light mechanisms, namely dispersive delay and stimulated Brillouin scattering, to dynamically compensate the group delay mismatch among different apertures, while we use optical phase locking to control the relative phases of the optical signals emitted from different apertures, as the system steers the beam in two dimensions. © 2012 Optical Society of America

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Light detection and ranging (LIDAR) is employed in a wide variety of sensing applications, such as measuring atmospheric properties, detecting chemical and biological agents, locating vehicles and measuring their speeds, and both aerial and bathymetric surveying [1].

Two key figures of merit for a LIDAR system are its transverse and longitudinal resolutions. The longitudinal resolution of a time-of-flight measurement is primarily determined by the duration τ_c of the emitted pulses. The transverse resolution is determined by the well-known Rayleigh criterion, scaling inversely with the aperture size of the emitter. Increasing the aperture size improves the transverse resolution but requires bulky opto-mechanical components that are power intensive and generally slow to steer. An alternative is to use a coherently combined phased array of small emitters to achieve a large effective aperture [2]. However, when the system is steered off-axis, each emitter sees a different path length to the far-field target. Specifically, the maximum optical group delay mismatch among all apertures is given by $\Delta\tau_{\mathrm{mis},i} = D_i \sin(\theta_i)/c$, where D_i and θ_i are the effective aperture size and the steering angle along the $i = x, y$ axis, respectively, and c is the velocity of light in air. This mismatch degrades both the longitudinal and transverse resolutions of the system, especially for a high-resolution system in which τ_c is comparable to or shorter than $\Delta\tau_{\mathrm{mis},i}$. Thus, it is crucial to dynamically correct the group delay mismatch in both x and y directions such that the pulses emitted from different channels reach the far field simultaneously as the beam is steered in two dimensions. It has been recently shown that one can use dispersive delay [3], in a manner also known as the fiber prism technique [4–6], to dynamically compensate the group delay mismatch for a phased-array LIDAR that scans the beam along one axis [7], but its extension to two-dimensional (2D) scanning is complex [8].

In this Letter, we propose and demonstrate a design for a multi-aperture slow-light laser radar (SLIDAR) system that can steer the beam in 2D. A schematic of our 2D SLIDAR system is shown in Fig. 1. We use three emitters and arrange them in a right-angle 2D pattern [see Fig. 1(a)]. Such a configuration requires us to simultaneously implement two independent group delay controls to compensate the delay mismatch in two orthogonal directions. Here, we choose dispersive delay and stimulated Brillouin scattering (SBS) slow light [9,10] for the x and y directions, respectively. The system also requires accurate optical phase control among all apertures. It therefore contains all of the conceptual difficulties of a multichannel 2D system.

To simulate a system with a full aperture of roughly a meter targeting objects over a kilometer away with 6 ns pulses, we have built a proof-of-principle setup that is roughly 1∶1000 in scale. The FWHM of each output beam is 2.1 mm, and the distance between neighboring emitters is 3.3 mm. We use two translation stages [see Fig. 1(b)] to move emitters 1 and 3 to mimic the group delay mismatch experienced when a full-scale system steers the beam in the x and y directions, respectively.

We start with a tunable laser source near 1550 nm and use an SBS generator to create our signal field. This ensures that the frequencies of the signal field and pump field always satisfy the SBS condition as one tunes the wavelength of the laser. Our SBS generator contains 3.3 km of dispersion-shifted fiber (DSF) with a Brillouin frequency shift Ω_B of approximately 10.5 GHz. Part of the laser output serves as the pump field at frequency ω, while part is intensity modulated at Ω_B using an electro-optic intensity modulator IM1 [see Fig. 1(c)] biased for minimum DC transmission. The output field from IM1 then propagates through the DSF, which is counter-pumped with a 19 dBm pump field at ω. The SBS process amplifies the Stokes field at $\omega - \Omega_B$ while attenuating the anti-Stokes field at $\omega + \Omega_B$. The extinction ratio between the Stokes field and other frequency components after this purification process is more than 20 dB, and we use this amplified Stokes field as our signal frequency field.

The Stokes field is then split into two parts [see Fig. 1(c)]. One part is frequency shifted by 55 MHz using an acousto-optic modulator (AOM) to produce a reference field for optical phase locking. The remainder of the Stokes field is modulated by IM2 to generate the signal pulses with FWHM of 6 ns. We set the DC bias of IM2 such that the signal pulse train still has a small constant optical background for use in phase locking.

For group delay compensation in the y direction, channels 1 and 2 contain 2.2 km of DSF, and channel

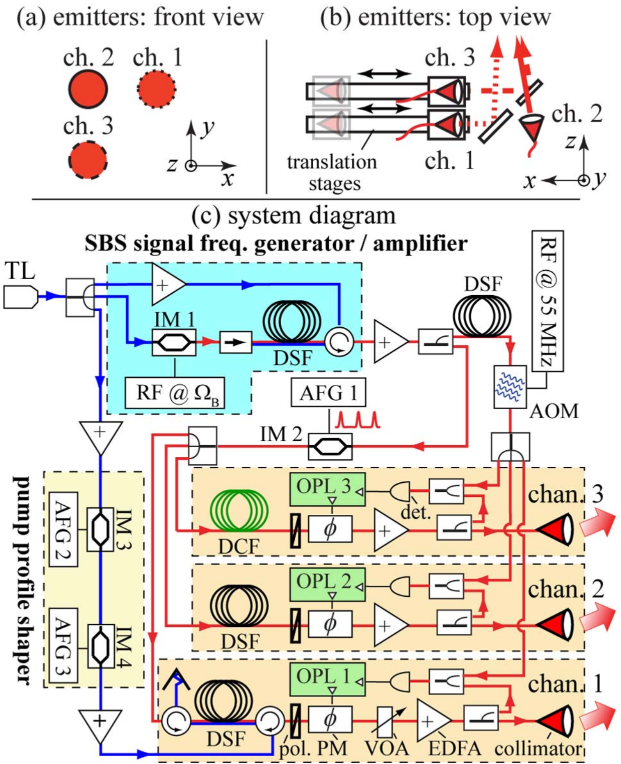

Fig. 1. (Color online) Schematic diagrams of a 2D SLIDAR system, including the top view (a) and front view (b) of the emitter array layout, and the remainder of the system (c). TL: tunable laser, EDFA: Erbium-doped fiber amplifier, OPL: optical phase locking circuit, POL: polarizer, PM: phase modulator, AOM: acousto-optic modulator, VOA: variable optical attenuator, AFG: arbitrary function generator, IM: intensity modulator.

3 contains 2.2 km of dispersion-compensating fiber (DCF). This results in a relative dispersive delay of −291 ps/nm between channel 3 and the other two channels. Group delay compensation is achieved by tuning the laser wavelength for different pointing angles in the y direction. To achieve group delay compensation in the x direction, we construct an SBS slow-light module using the DSF in channel 1 with a counterpropagating pump field. The FWHM bandwidth of our 6 ns signal pulses is approximately 73 MHz, which is larger than the measured 20 MHz intrinsic SBS linewidth of the DSF. To minimize signal distortion, we use a two-stage pump modulation method [11] to achieve a broadened flat-top SBS gain profile (see Fig. 2) for positive group delay. Here the frequencies of the sinusoidal signals driving IM3 and IM4 are 22 and 23 MHz, respectively. Negative time delay can be achieved with different modulation RF signals using the same setup [11]. Once the desired shape of the gain profile is obtained, tunable delay is achieved by controlling the power of the pump field. The standard deviation of the measured SBS delay due to pump power fluctuation is typically less than 2% of the pulse width [11].

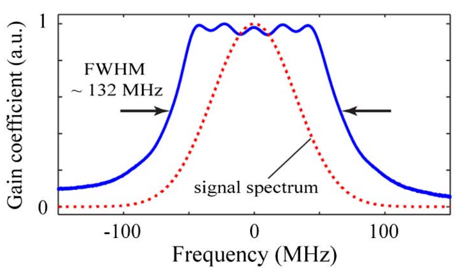

Fig. 2. (Color online) Measured SBS gain coefficient as a function of frequency detuning. The red dotted line shows the spectrum of Gaussian pulses with FWHM of 6 ns.

For phase control, a small portion of the signal immediately before the final output of each channel is split off and mixed with the 55 MHz-shifted optical reference field. The detected beat signal is sent to a phase locking circuit, which feeds back to an electro-optic phase modulator in each channel [7,12]. Further details of the phase locking procedure will be published elsewhere.

An erbium-doped fiber amplifier (EDFA) is used near the end of each channel to maintain constant signal output power from each emitter. The output of each channel is directed using adjustable mirrors to a retro-reflecting target approximately 6 m from the emitters. In our experiment, the returned optical signal is collected using a lens and a photodetector located near the emitters. In a full-scale system, multiple steered receiving apertures can be used and be arranged compactly to avoid the need for additional delay modules, since the detection is not an imaging process and therefore the detection efficiency is only determined by the total collecting area.

We have performed a series of tests to demonstrate our SLIDAR system. Figure 3(a) shows a far-field intensity pattern when the phase locking is turned on. The contrast ratio of the pattern is quite high, indicating robust phase locking among all three channels. The RMS phase jitter of the locked signal is approximately $\lambda/10$ whether the SBS delay module is turned on or off [12].

We then demonstrate the 2D beam steering with group delay compensation. The translation stages are first positioned to simulate "straight ahead" targeting. When the wavelength is set to 1530 nm, the signals from the three channels are perfectly overlapped [see Fig. 3(b)]. In Fig. 3(c), a tilt in the y direction is simulated using the

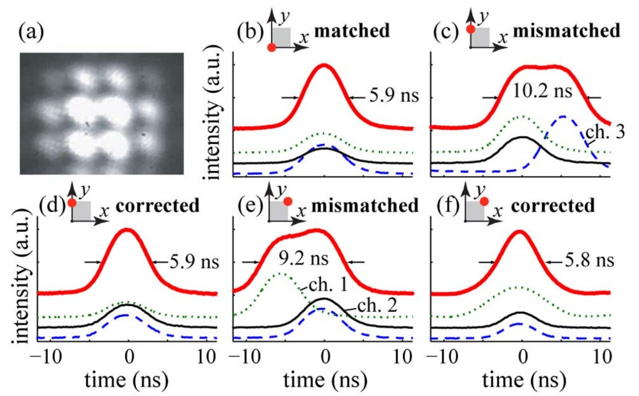

Fig. 3. (Color online) Phase-locked far-field intensity pattern of our SLIDAR system (a) and the normalized time traces (b)–(f) of the returned signal when the beam is steered in three directions (indicated by the red dot at the top of each subfigure) with or without group delay compensation. The thick solid line is the combined signal, and the dotted, thin solid, and dashed traces correspond to signals emitted individually from channels 1, 2, and 3, respectively. The traces are shifted in the y direction for clarity.

translation stage on channel 3. The resulting delay mismatch between channel 3 and the other two channels results in significant pulse broadening to 10.2 ns. The group delay mismatch is compensated using dispersive slow light by tuning the wavelength of the system to 1549.5 nm [see Fig. 3(d)]. We then apply an additional simulated steering in the x direction using the translation stage in channel 1. This creates an additional group delay mismatch between channel 1 and the other channels [see Fig. 3(e)], which is then corrected using SBS slow light with a pump power of 240 mW [see Fig. 3(f)]. Since the two delay mechanisms are independent, we can dynamically correct the group delay for any 2D beam pointing angle smaller than the extreme cases demonstrated here by choosing appropriate wavelength and SBS pump power. The group delay tuning speed of the SBS module is mainly limited by the transit time of the counterpropagating pump through the SBS module, which is approximately 10 μs in our system. The tuning speed of the dispersive delay module is determined by the wavelength tuning speed of the laser, which can be up to 25 nm/μs using, e.g., a Fourier domain mode locking laser [13].

In conclusion, we have designed a three-channel SLIDAR system with a 2D aperture array layout. Using two independent slow-light mechanisms, namely dispersive delay and SBS, we have dynamically compensated the group delay mismatch among different apertures during beam steering in both x and y directions, while simultaneously maintaining control over the relative optical phases of the three channels.

For a system with more than three apertures, one can design a 2D grid of delay modules. For example, a single multitapped SBS delay line can provide horizontal delays, with each tap feeding a tapped dispersive delay line that provides the appropriate vertical delays to each emitter. The operation of the SBS and dispersive delay modules remains the same, with SBS pump power and laser wavelength controlling the x and y delay compensation simultaneously for all apertures. Note also that for dense arrays, each delay channel can be used to feed multiple neighboring emitters, since it is not necessary to control the group delay as precisely as the phase.

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