Free-space ballistic laser propagation of a pulse coded data stream through fog

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We describe the use of space and polarization gates in a study of free-space optical communication of a coded pulse train as it passes through turbid media. The propagation of coded signals at 10 GHz through adverse environmental conditions is demonstrated. Polarization and space-gating techniques are used to improve the signal-to-noise ratio and to enhance the information fidelity of high-bit-rate transmitted signals, which shows potential improvement for cloud, fog, and smog applications. © 2003 Optical Society of America

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Free-space optical (FSO) technology has been in existence for nearly four decades. Recently, however, FSO has experienced unprecedented growth due to needs of last-mile users who have demanded high-speed data connectivity in their homes and offices.[1,2] Although microwave- and radio-based systems provide a partial solution to the bottleneck restricting high-speed data connectivity into homes and offices, wireless optical communication gives access to a much greater bandwidth (0.1–1 Gbps). Indeed, by the year 2006, FSO is expected to be a multibillion dollar market.[2] FSO can be implemented with wavelength division multiplexing with ultrawide supercontinuum band tunable femtosecond laser sources. The large bandwidth available through wireless optical communication can operate without the licensing that limits the future of radio or microwave systems. Fiber-optic systems can provide an even greater bandwidth (2.5–40 Gbps) link that is competitive with FSO communication. As the optical fiber attenuates the signal at a predictable rate, it is possible to amplify and compensate the signal. Fiber-optic communication is preferred for long-haul system and backbone networks. For metropolitan networks, however, FSO communication has the advantage of inexpensive equipment, easy and fast deployment, and flexible service rollouts in any network topology. Moreover, FSO technology offers bandwidth capabilities extending into the terabit-per-second and petabit-per-second range.

Unfortunately, under different weather conditions scattering and absorption attenuate the transmitted wireless optical signal in an unexpected way, which limits FSO's application in long-haul systems. The major disadvantage stems from multiple scattering, which broadens the signal's temporal response. The broadened signals overlap with each other, causing a degradation of information and a limitation on the ultimate bandwidth that can be used. A pulse laser source, which represents the signal "1" with a much narrower laser pulse, has several advantages over a modulated cw laser when signals are transmitted through atmospheric environments. Because the narrow pulse has a much higher energy intensity, the signal can survive a longer distance before it is attenuated. When an ultrafast laser pulse propagates through a turbid media (e.g., cloud, fog, or smog), the detected pulse broadens into early and diffusive components in the temporal domain. The early component includes a ballistic component[3] and a snake component,[4] which are usually buried in the diffusive light background from the previous pulses. The ballistic and snake components carry the original data information sent by the source and are considered to be the signals. Several techniques can be used to discriminate the data signal[5,6] from the diffusive light, which acts as the noise. The space and polarization gates use the randomization properties of the propagation direction as well as the polarization state

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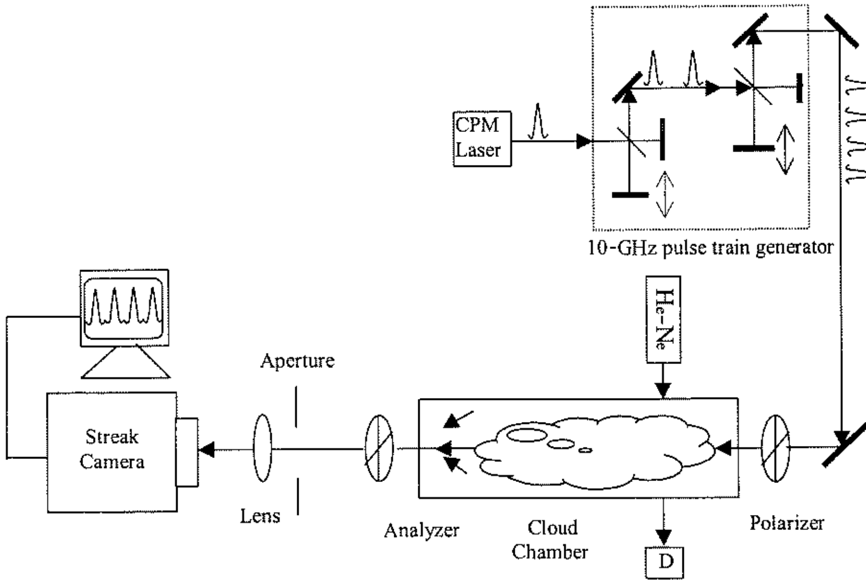

Fig. 1. Schematic diagram of the experimental setup.

of the diffusive light due to multiple scattering. A space gate is used to restrict the angular emission along the received direction that excludes diffusive photons from directions other than the source. The polarization gate makes use of the fact that ballistic and snake photons retain their polarization memory, whereas the diffusion component is depolarized by the scattering events of an incident beam of polarized light. The time gate technique,[7] which needs a reference light to select the ballistic and snake components, can be performed with a timing autotracking pulse beam that can also help compensate for building sway.

In this paper we investigate the use of space and polarization gates to a 10-GHz pulse coded train after it passes through a fog medium. To select the ballistic component, the off-axis diffusive component is rejected by the apertures in the incident light direction. A polarization analyzer is used to extract the ballistic photons with polarization parallel to the incident polarization and to filter out the diffusive photons with different polarizations. By combining these two techniques, we demonstrate a significant improvement in the ballistic pulse signal detection in a dense fog medium.

The attenuation of the ballistic light passing through the atmosphere is described by

$$I = I_0 \exp(-\mu_t L_m), \qquad (1)$$

where I and I_0 are the detected and source light intensities, respectively; μ_t is the extinction coefficient (the extinction coefficients due to light scattering and absorption from the particles $\mu_t = \mu_s + \mu_a$); and L_m is the distance between the light source and the detector.

The visibility[8,9] (S_v) is a measure of the effect of obscurants in the atmosphere. The visibility through the fog is the maximum distance at which the human eye can see a large, dark object. S_v is determined primarily by the object's visual contrast with the background. The contrast is caused by differences in both color and brightness (intensity); however, since atmospheric visibility in cloud, fog, and smog is restricted by large particles that scatter all colors equally, and since most objects are dark compared with the sky, we consider only brightness differences. The minimum brightness contrast that an average human being can distinguish is approximately 2%. The visibility is equal to the distance at which the apparent brightness of the object differs from the brightness of the background by 2%. The visibility is given as

$$S_v = \frac{3.9}{\mu_t} = 3.9 l_t, \qquad (2)$$

where l_t is the total extinction mean free path (l_t due to the scattering mean free path and the absorption mean free path $\mu_t = 1/l_t = 1/l_s + 1/l_a$).

The experimental arrangement used to test the gating method is shown in Fig. 1. Ultrafast 100-fs laser pulses are generated at a repetition rate of 82 MHz by a colliding pulse mode-locked dye-laser (CPM) system. The laser power is set at 5 mW, with a wavelength centered at 620 nm. The polarized laser beam is collimated and incident into a 182 cm × 15 cm cylindrical fog chamber that uses nebulizers and commercial fog generators (UL Fogger 700 by NESS). Two sets of the Michelson-interferometer-like setup are used to generate a pulse train of four pulses. These four pulses are the signals. The duration between two pulses can be adjusted by changing the distance of the arms in the setup. We set the duration to 100 ps in this experiment, which corresponds to a repeat rate of 10 GHz. The analyzer can be used to select the transmitted light parallel to the incident polarization state. A lens of 5-cm focal length is used to focus the ballistic and scattered light in the transmitted direction to the slit of the streak camera. The aperture immediately in front of the streak camera and the slit inside the streak camera together act as the spatial gate. The spatial, temporal, and polarization profiles of the pulse train are recorded by the Hamamatsu streak camera. A He–Ne laser and a powermeter are arranged to simultaneously monitor the fog density and to estimate the beam attenuation. The length of the fog chamber is 182 cm. The visibility of the fog is calculated from Eqs. (1) and (2):

$$S_v = \frac{3.9L_m}{\ln I_0 - \ln I}, \tag{3}$$

where L_m is the diameter of the chamber, which is 15 cm. The experiment is conducted in heavy fog over a distance of 182 cm, where the number of scattering events is $L/l_t = 31$.

Because of the long visibility in the atmosphere, a laboratory scale test experiment was performed with a much denser atmosphere environment. One can rescale our results from the laboratory environment to the atmosphere environment in which S_v is much larger and the scattering concentration is much lower.

Figures 2–4 show the recorded profiles of the pulse train in the density situation of $S_v = 22.7$ cm ($l_t = 5.8$ cm) under different gate conditions. The horizontal direction represents the time, and the vertical direction represents the space. The curve is the accumulated intensity of the received light along the space (vertical direction). Figures 2 shows the temporal intensity profiles recorded by the streak camera with a wider slit (120 channels) without an analyzer. Clearly, the background noise, which is contributed by the multiple scattered light, impairs the transmitted information. The signal-to-noise ratio (S/N) is low (~0.6) in this case. The diffuse background noise present before the first ballistic pulse arrived is contributed by the previous four pulses because of the 82-MHz repetition rate of the CPM. Figure 3 illustrates the temporal profiles when a polarization filter selects the parallel component of the signal. Compared with the profile shown in Fig. 2, the background noise here is greatly reduced. This improvement arises from a reduction in the background noise of the perpendicular-to-incident polarization component, which is reduced by the analyzer. Additionally, some noise is reduced by the analyzer to an intensity level below the detection threshold of the streak camera. The S/N is increased from 0.6 to 3. The temporal profile in Fig. 4 uses a space gate by selecting a narrower spatial window (16 channels instead of 120 channels, as illustrated in Fig. 3), as well as an aperture space gate and a polarization filter. The slit cuts mainly the off-axis light that passes through the finite-sized aperture. The end result is a marked reduction in the background noise and an increase in the S/N to 14.

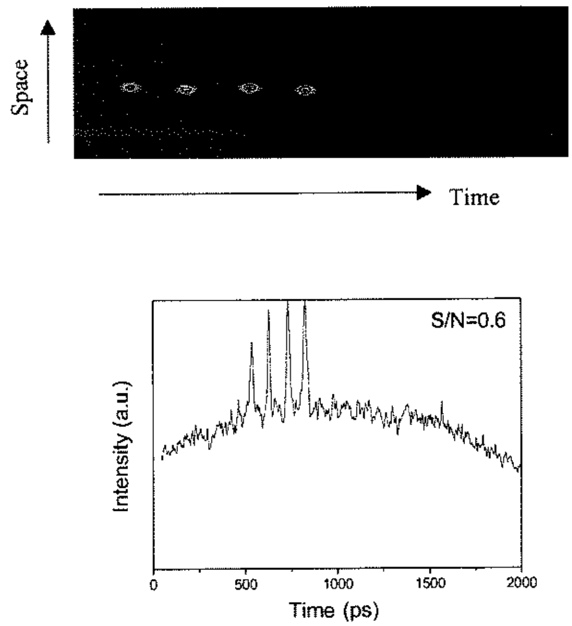

Fig. 2. Temporal profiles of the pulse train measured with a streak camera. Profiles are recorded without an analyzer and with a wider streak camera slit (120 channels).

These results demonstrate that 10-GHz signals traveling a distance of $8.0S_v$ can be clearly extracted by using space and polarization gates. The visibility in hazy (<2.8 km) and foggy (<500 nm) weather[10] is excellent for local optical networks. As a last-mile solution, the application of space and polarization gates to optical wireless communication is very promising. Future experiments conducted over longer transmission distances will

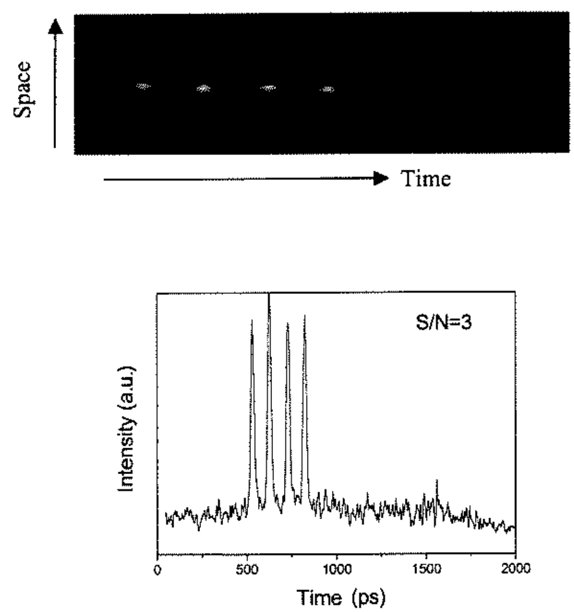

Fig. 3. Temporal profiles of the pulse train recorded with an analyzer oriented parallel to the polarizer axis and with a wider streak camera slit (120 channels).

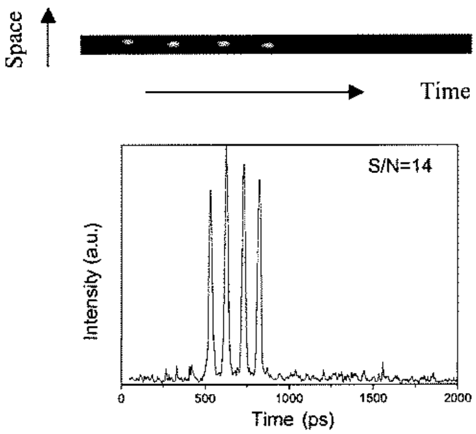

Fig. 4. Temporal profiles of the pulse train recorded with an analyzer oriented parallel to the polarizer axis and a space gate of a narrower streak camera slit (16 channels).

benefit from the polarization analysis technique,[11] which can eliminate the effect of that part of the diffusion component that propagates in the same direction as and maintains the same polarization state as the incident light. The laser wavelength is another key parameter that will affect the signal transmission distance. Compared with the visible light center at 620 nm, near-infrared lasers will experience less atmospheric attenuation and an added improvement from slight absorption.[12] Self-mode-locked Cr^{4+}-doped lasers[13] can generate 50-fs pulses tunable from 1240 to 1270 nm, and from 1350 to 1550 nm. These tunable lasers in compact form are ideal pulse laser sources for future free-space wireless optical communication applications.

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