Incoherent-light temporal imaging

Bo Li and José Azaña

Institut National de la Recherche Scientifique – Energie, Matériaux et Télécommunications (INRS-EMT) Montreal, Québec, H5A 1K6 Canada
Author e-mail address: bo.li@emt.inrs.ca

Abstract: We propose and experimentally demonstrate the first incoherent-light scheme for temporal imaging, including time-to-frequency mapping, temporal magnification and compression, of high-speed intensity waveforms.

OCIS codes: (070.1170) Analog optical signal processing. (320.7085) Ultrafast information processing.

Temporal imaging [1, 2] and related concepts provide new, unique opportunities for generation [3], measurement [4], cloaking [5] and processing [6] of time-domain waveforms across a wide range of frequency regimes, from radio-frequency (RF) signals [6] to ultrafast optical information [3-5]. Temporal imaging systems developed to date are based on suitable combinations of dispersive processes and time lenses, and they essentially rely on coherent optics, thus requiring the use of broad-bandwidth pulse sources (e.g. mode-locked lasers [3-6]) and precise coherent amplitude and phase control of the involved signals [1-6]. These requirements represent a fundamental hurdle to the practical use of these methods. Temporally incoherent light sources are significantly simpler and more affordable than their coherent counterparts, while inherently providing the large frequency bandwidths that are needed for highly-performing temporal imaging systems. Mechanisms have been demonstrated for temporal dispersion of incoherent intensity waveforms [7]; however, no system based on time lenses has been previously realized using an incoherent lightwave approach. Here we propose and experimentally demonstrate the first incoherent-light scheme for temporal imaging, including time-to-frequency mapping, temporal magnification and compression, of intensity waveforms. As an example, we report demonstration of temporal imaging of high-speed RF waveforms with a time-bandwidth product (TBP) exceeding 160, i.e., resolution of ~50 ps over a temporal aperture >8 ns, using illumination with an 11.6-nm-bandwidth incoherent light source and a temporal pinhole with a duration of ~146 ps. The performance specifications of the demonstrated system are similar to those offered by previous schemes aimed at the same goal, so-called temporal stretching systems [6], but totally avoiding the need for broadband pulsed laser source. Our proposal opens up entirely new possibilities for a new class of incoherent-light-based signal processors.

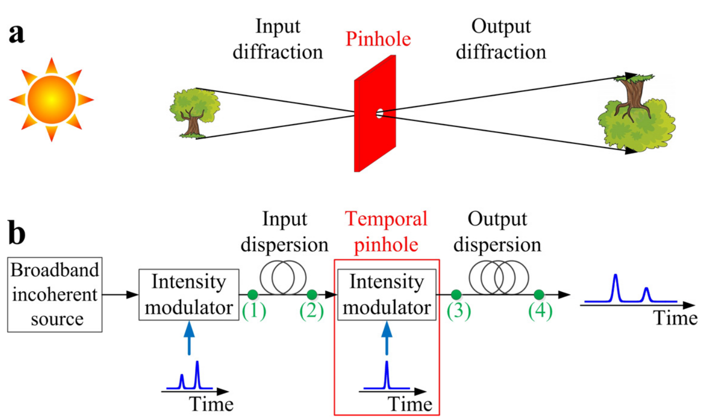

Fig. 1 Incoherent temporal imaging concept. a, Illustration of an incoherent spatial imaging system based on free-space diffraction and a pinhole. b, Propose scheme of incoherent temporal imaging, which is constructed as the temporal equivalent of the incoherent-light pinhole camera, involving temporal group-velocity dispersion and intensity modulation with a fast temporal shutter (temporal pinhole).

An illustration of the proposed scheme for incoherent temporal imaging is shown in Fig. 1b. Our approach is based on implementing a time-domain equivalent of a classical pinhole camera illuminated by a totally incoherent light source, represented in Fig. 1a. Briefly, in relation to the scheme in Fig. 1b, light from a broadband, temporally incoherent light source is modulated in intensity by the input waveform to be processed. The modulated light is firstly dispersed by an input first-order dispersion, essentially a medium or device providing a predominantly linear group-delay variation $\ddot{\Phi}_{In}$ over the entire bandwidth of the light source. This is followed by a second temporal intensity modulation process with a short pulse waveform, implementing the time-domain equivalent of a spatial pinhole. The resulting modulated light wave is finally dispersed through a second (output) first-order dispersive line, characterized by a linear group-delay $\ddot{\Phi}_{Out}$. As shown in Fig. 1b, the averaged optical intensity at the system output is a temporally scaled (magnified or compressed) image of the input intensity waveform, with a magnification factor $M = -\ddot{\Phi}_{Out} / \ddot{\Phi}_{In}$.

Fig. 2 shows the experimental results on incoherent temporal magnification (c-e) and temporal compression (f-h). The intensity profile of the temporal pinhole and the spectrum of the incoherent light source used in these two experiments are shown in Fig. 2a and 2b, respectively. *For temporal magnification*, the input and output dispersions are –692 ps/nm and 1981 ps/nm, respectively. The averaged output intensity waveform (solid black) is a magnified temporal image of the input intensity waveform (dotted blue), with the expected magnification factor of M = 2.86, all along a temporal aperture of ~8.1ns, as represented in Fig. 2c. The measured input resolution is estimated as ~49.3 ps. Time-to-frequency mapping has been also achieved, as demonstrated through the comparison between the optical spectrum (solid red in Fig. 2d) measured at the output of the temporal pinhole and the input optical waveform (dotted blue). Fig. 2e shows the temporal intensity profile of the output image without averaging. *For temporal compression*, there is an excellent agreement between the output temporal intensity profile in average (solid black) and the input optical waveform (dotted blue), as demonstrated in Fig. 2f. The input and output dispersions are 1981 ps/nm and –692 ps/nm, respectively, resulting in a compression factor of 2.86. The output temporal aperture and output resolution are 8.1 ns and 51.25 ps, respectively. In terms of time-to-frequency mapping, there is again an excellent agreement between the output spectrum in average (solid red) and the input optical waveform (dotted blue), as shown in Fig. 2g. Fig. 2h shows the temporal intensity profile of the output image without averaging.

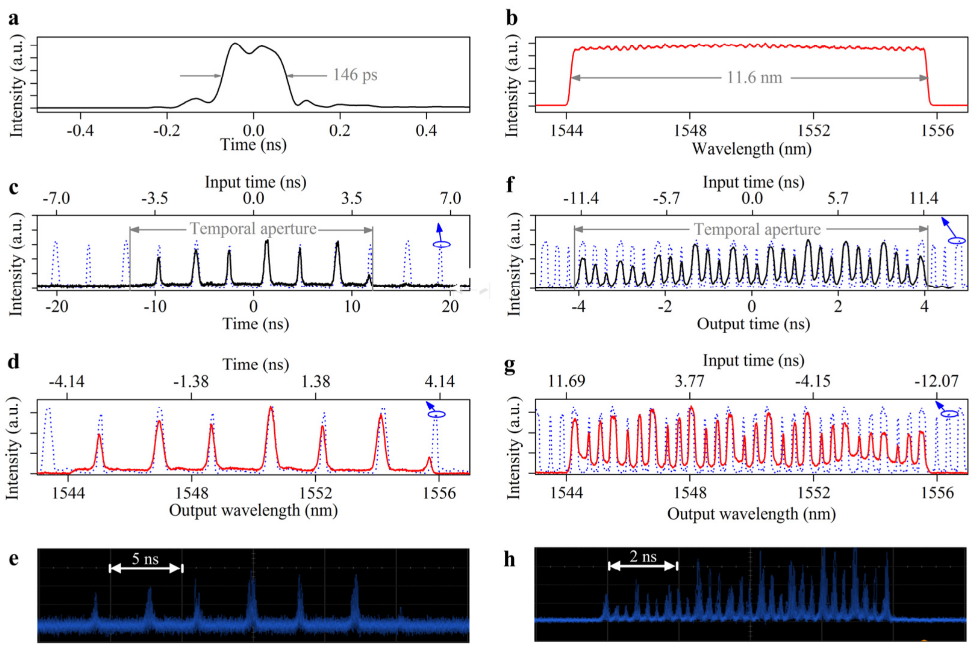

Fig. 2. Experimental demonstration of incoherent temporal magnification (c-e) and temporal compression (f-h). a, Intensity profile of the temporal pinhole. b, Spectrum of the incoherent light source. c, f, Temporal intensity profiles of the outputs in average (solid black) and corresponding scaled inputs (dotted blue). d, g, Output spectra in average (solid red) versus scaled input waveforms (dotted blue). e, h, Temporal intensity profiles of the outputs without averaging. The averaging time for each waveform shown in a-g is 256.

In summary, we have demonstrated time-to-frequency mapping, temporal magnification and compression of incoherent light intensity waveforms using the time-domain equivalent of a spatial pinhole camera. The demonstrated concept could open the path for realization of a wide variety of novel incoherent-light-based high-speed signal generation, processing, cloaking and detection instruments by using the wealth of knowledge developed for coherent temporal imaging and related schemes.

References

[1] B. H. Kolner, "Space-time duality and the theory of temporal imaging," IEEE J. Quantum Electron. **30**, 1951-1936 (1994).
[2] B. H. Kolner, "The pinhole time camera," J. Opt. Soc. Am. A **14**, 3349-3357 (1997).
[3] J. van Howe, J. Hansryd, and C. Xu, "Multiwavelength pulse generator using time-lens compression," Opt. Lett. **29**, 1470-1472 (2004).
[4] M. A. Foster, et al., "Silicon-chip-based ultrafast optical oscilloscope," Nature **456**, 81-84 (2008).
[5] M. Fridman, A. Farsi, Y. Okawachi, and A. L. Gaeta, "Demonstration of temporal cloaking," Nature **481**, 62-65 (2012).
[6] Y. Han and B. Jalali, "Photonic time-stretched analog-to-digital converter: Fundamental concepts and practical considerations," J. Lightwave Tech. **21**, 3085-3103 (2003).
[7] C. Dorrer, "Statistical analysis of incoherent pulse shaping," Opt. Express **17**, 3341-3352 (2009).