

Incoherent-light temporal compression of microwave signals using a ‘time-domain eye’ system

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Abstract: We propose a novel design for temporal imaging, combining the advantages of using incoherent light (long aperture) and a time lens (high resolution). We demonstrate temporal compression of microwave signals with a time-bandwidth product >300 .

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Temporal imaging (including stretching and compression) [1, 2] have been used for generation [3], measurement [4] and processing [5] of electronic and radio-frequency (RF) signals [3, 5], and ultrafast optical information [1, 2, 4]. These systems are achieved by suitably combining dispersion and time lenses. To evaluate the main figure of merit of a time-lens based system, it is common to use the time-bandwidth product (TBP), which is the product of temporal aperture (typically defining the maximum duration of the signal under analysis) and operation frequency bandwidth (typically defining the system temporal resolution) [2]. However, to achieve a long temporal aperture over a large frequency bandwidth, i.e. for a TBP above 10, broadband coherent pulsed sources, with bandwidths approaching or exceeding 10 nm [2-5], are typically required. Recently, an incoherent-light temporal imaging system, well suited for processing microwave signals, has been experimentally demonstrated [6]. This system is based on a combination of dispersion and a temporal pinhole, which can be realized by temporal gating with a short pulse waveform [6]. Compared with coherent light, temporally incoherent light is inherently broadband and can be generally produced in a simpler and more affordable fashion and as such, a very high TBP of ~ 160 has been demonstrated [6]. However, this incoherent-light temporal imaging system is ultimately limited by its relatively *poor resolution* (~ 50 ps in the experiments reported in Ref. [6]), particularly as compared with conventional time-lens-based systems [1-6]. In this paper, we propose a novel incoherent-light design for temporal imaging of intensity waveforms (e.g., microwave signals), incorporating a time lens to improve the system time resolution without affecting its intrinsically long temporal aperture.

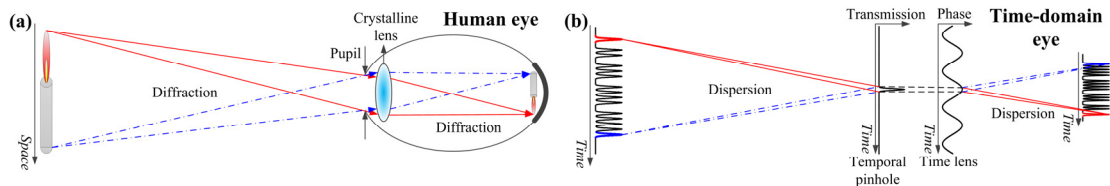


Fig. 1 Space-time duality. (a) Illustration of incoherent-light spatial imaging based on spatial diffraction and a human eye. (b) Illustration of the proposed scheme for temporal imaging, using a temporal counterpart of the human eye system.

Fig. 1(a) shows the scheme of a well-known incoherent-light spatial imaging scheme, namely that used by the human eye. In particular, the pupil and the crystalline lens of the human eye work as a spatial pinhole and a spatial thin lens, respectively. The novel temporal imaging design proposed here can be interpreted as a time-domain equivalent of the human eye system shown in Fig. 1(a). Our design consists of a temporal pinhole followed by a time lens; incoherent temporal imaging can be achieved by combining dispersion and the ‘temporal eye’, as shown in Fig. 1(b). In relation to Fig. 1(b), broadband incoherent-light is modulated in intensity by the input intensity signal (e.g., microwave signal) to be processed. The modulated light firstly propagates through a dispersive line, which provides a linear group-delay with a slope $\ddot{\Phi}_{In}$. The dispersed light is then sent through the temporal intensity modulator implementing the temporal pinhole. Subsequently, the modulated light is sent through a time lens, which imparts a quadratic phase across the temporal signal, i.e., $\varphi_{TL}(t) = -t^2 / (2\ddot{\Phi}_{TL,f})$, where $\ddot{\Phi}_{TL,f}$ represents the focal group-delay dispersion of the time lens. In particular, the imaging condition is given by $1/\ddot{\Phi}_{In} + 1/\ddot{\Phi}_{Out} = 1/\ddot{\Phi}_{TL,f}$. The resulting light wave is finally dispersed through a second dispersive line, with a group-delay dispersion of $\ddot{\Phi}_{Out}$. At the system output, the *averaged* optical intensity is a temporally scaled (magnified or compressed) image of the input intensity waveform, where the scaling (magnification factor) is given by $M = -\ddot{\Phi}_{Out} / \ddot{\Phi}_{In}$. In the absence of a time-lens [6], the optimal resolution depends on the input and output dispersion values and is typically limited by the temporal pinhole duration. In sharp contrast, the output temporal resolution of our newly proposed design is inversely proportional to the pinhole duration; in particular, the resolution is given by $\delta\tau_{Out} \approx (4 \ln 2 |\ddot{\Phi}_{Out}|) / \Delta T_P$, where ΔT_P is the intensity FWHM of the temporal pinhole, assuming that this has a Gaussian-like profile. The input temporal aperture is given by $T_A = 2\pi |\ddot{\Phi}_{In}| \Delta f_{opt}$, where Δf_{opt} is the source bandwidth.

Fig. 2(a) shows the used experimental setup. Broadband incoherent light with a nearly uniform spectrum, centered at a wavelength of 1549.9 nm over a bandwidth of ~ 11.6 nm [see Fig. 2(b)], is generated by spectrally filtering the optical output from a superluminescent diode and then amplified by a semiconductor optical amplifier. The input incoherent optical signal to be imaged is obtained by a 40-GHz electro-optic intensity modulator, which is driven by the microwave signal under analysis. The microwave signal is generated by a 12-GHz electronic arbitrary waveform generator and then amplified by a 12-GHz electronic amplifier. Fig. 2(c) gives an example of input temporal waveform, i.e., a periodic two-pulse sequence of Gaussian-like pulses. The two different consecutive pulses have FWHM of 214.7 ps and 108.8 ps, respectively, and their time separation is 1.17 ns. The modulated light is sent through the input dispersive line with a dispersion of 1981 ps/nm and the time-domain pinhole. The temporal pinhole is implemented by another 40-GHz electro-optic intensity modulator driven by an electronic pulse waveform generated by the same arbitrary waveform generator, subsequently amplified by a 12.5-GHz electronic amplifier. Fig. 2(d) shows the measured averaged output waveform from the temporal pinhole, which has a nearly Gaussian-like shape with an intensity FWHM of ~ 161 ps. After the temporal pinhole, the light is sent through an electro-optic phase modulator, which works as a time lens. The measured temporal waveform (solid black) of the electronic drive for the phase modulator is illustrated in Fig. 2(e), which has a good agreement with the theoretical quadratic profile [dashed grey, calculated by Eq. (1)]. Finally, the modulated light is sent through the output dispersion (-692 ps/nm), and it is subsequently detected by a 45-GHz photo-detector and measured by an 80-GHz sampling oscilloscope and a 28-GHz real-time oscilloscope. As shown in Fig. 2(f), the *averaged* output intensity waveform is a scaled temporal image of the input intensity waveform, with the expected compression factor of $C = 1/M = 2.86$, along the 8-ns output temporal aperture. The measured temporal resolution is given by ~ 25.9 ps. Therefore, a TBP of 308.9 is experimentally obtained. Fig. 2(g) shows the temporal intensity profile of the output image without averaging.

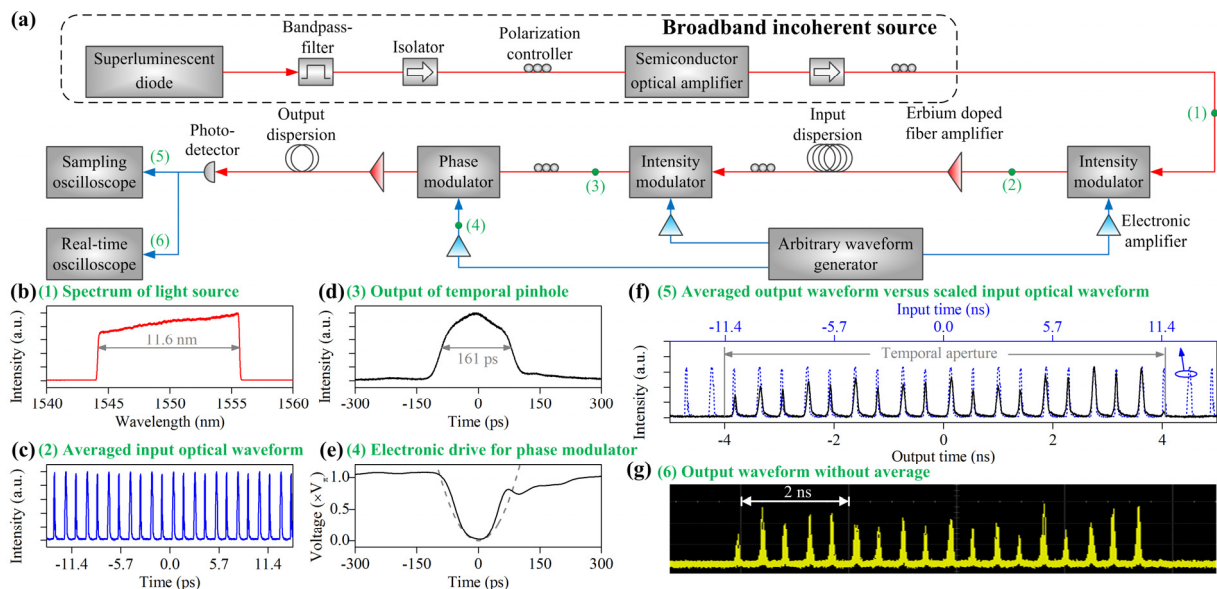


Fig. 2 Experimental setup for incoherent-light temporal compression and output waveforms along the system. (a) Experimental configuration. (b) Spectrum of the broadband incoherent light source. (c) Input optical temporal waveform. (d) Optical output from the temporal pinhole. (e) Measured electronic drive (solid black) for phase modulation, compared with the theoretical profile (dashed grey). (f) Temporal intensity profile (solid black) of the output image compared with the scaled input temporal waveform (dashed blue), where the scaling between input time and output time is 2.86. All profiles in (c)-(f) are measured using a sampling oscilloscope and averaged for 256 times. (g) Temporal intensity profile of the output image without averaging, which is measured by a real-time oscilloscope.

In summary, we have proposed and demonstrated incoherent-light temporal imaging (compression) of intensity waveforms using the time-domain equivalent of a human eye optical-imaging system. Whereas a TBP of ~ 300 has been already achieved in our proof-of-concept experiment, this is still practically limited by the available phase modulation amplitude in the used time lens: the value used in this experiment is only $\sim 1.1\pi$ and this could be readily increased to several tens of π . This incoherent-light temporal imaging concept can be applied for both temporal compression and magnification of high-speed microwave signals.

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