INCOHERENT-LIGHT TEMPORAL IMAGING OF HIGH-SPEED, LONG-DURATION MICROWAVE SIGNALS

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ABSTRACT

We review recent work on incoherent-light temporal imaging of intensity waveforms (e.g., high-speed microwave signals). In a relevant example, we create a temporal pinhole camera to demonstrate temporal magnification (stretching) of microwave waveforms modulated on incoherent light, obtaining a magnification factor of 2.86, with a resolution of ~50 ps over a temporal aperture of ~8 ns, totally avoiding the use of chirp-controlled pulsed lasers.

Keywords: *Analog optical signal processing, Ultrafast information processing, Temporal imaging.*

1. INTRODUCTION

The space-time duality theory arises from the mathematical equivalence between free-space diffraction of a spatial field and chromatic dispersion of a temporal field. Based on this basic duality, temporal imaging and related concepts have been proposed as time-domain equivalents of spatial imaging [1, 2], and have been used for generation [3], measurement [4], cloaking [5] and processing [6] of time-domain waveforms, such as electronic and radio-frequency (RF) signals [3, 6], and ultrafast optical information [4, 5]. Among these systems, a key element is a time lens, which is a time-domain equivalent of a spatial lens. A time lens is conventionally implemented by electro-optic phase modulation or parametric processes.

The performance of time-lens-based systems is evaluated in the form of time-bandwidth product (TBP), or the number of resolvable points and it essentially depends on the time-lens frequency bandwidth [1]. To realize a high-performance time-lens system offering TBPs > 10, broadband (short-pulse) coherent light pulses, with bandwidths typically approaching or exceeding 10 nm, combined with precise control of the pulses' phase chirp are required [1-6]. Such requirements represent a critical practical hurdle. Thus, incoherent-light implementation of space-time duality concepts is of particular interest [7, 8], as temporally incoherent light could inherently provide large bandwidth and can be generally produced in a simpler fashion than its coherent counterpart.

Here we provide an overview of our recent work on the first practical schemes for temporal imaging (magnification) of incoherent-light intensity waveforms [9-11]. In this communication, we report temporal imaging results with TBPs around 160, i.e., resolution of ~50 ps over a temporal aperture of ~8 ns, avoiding the use of broadband pulsed laser sources and their coherent phase chirp control. Our schemes are particularly useful for temporal stretching of high-speed RF waveforms, a functionality that has been widely investigated to adapt the bandwidth of RF signals to available detection or measurement instrumentation [3, 6].

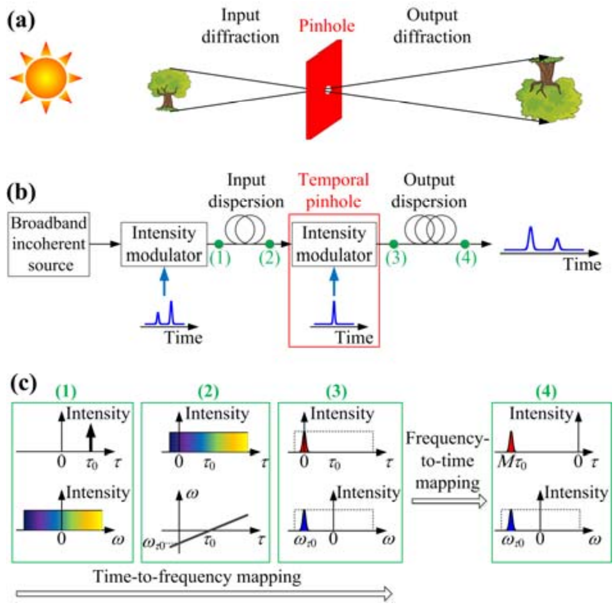

Fig. 1. (a) Illustration of an incoherent-light spatial imaging system (pinhole camera). (b) Proposed scheme for incoherent-light temporal imaging, which is constructed as the temporal equivalent of the incoherent-light pinhole camera. (c) Illustration of the impulse response of the temporal imaging system in (b), ignoring group delays. All represented temporal waveforms and spectra, and the instantaneous frequency curve, are averaged profiles.

2. PRINCIPLES

Fig. 1(b) shows an illustration of our first proposed scheme for incoherent-light temporal imaging [9]. Our approach is based on a time-domain equivalent of a classical pinhole camera illuminated by incoherent light [12], represented in Fig. 1(a). The idea of a temporal pinhole camera was first proposed and investigated by Kolner at the theoretical level [2]. However, in a temporal pinhole camera, the system performance, particularly temporal aperture and the related TBP, is directly dependent of the input signal features (frequency bandwidth), thus being generally limited to processing ultrashort pulse waveforms [2]. Our work has shown how the temporal pinhole concept holds the key for development of incoherent-light temporal imaging and related systems with greatly improved performance. In relation to Fig. 1(b), light from a broadband, temporally incoherent optical source is modulated in intensity by the input waveform to be processed. The modulated light first propagates through a dispersive line, a medium or device providing a predominantly linear group-delay variation, with a slope $\ddot{\Phi}_{In}$, over the entire optical bandwidth. This is followed by temporal intensity modulation with a short pulse waveform, implementing the time-domain pinhole. The resulting modulated lightwave is finally dispersed through a second dispersive line, characterized by a linear group-delay with a slope $\ddot{\Phi}_{Out}$. The *averaged* optical intensity at the system output is a temporally scaled (magnified or compressed) image of the input intensity waveform.

The proposed incoherent temporal imaging process consists of two main steps, namely time-to-frequency mapping of the input intensity waveform, implemented at the output of the temporal pinhole, followed by dispersion-induced frequency-to-time mapping. Time-to-frequency (frequency-to-time) mapping refers to a process by which the input temporal waveform (spectrum) is transferred into the output spectrum (temporal waveform). These two steps can be easily visualized through an analysis of the system temporal impulse response, as illustrated in Fig. 1c. Assuming that the light source is totally incoherent (white noise), with a uniform energy spectrum, one can show that the incoherent system in Fig. 1b is linear in intensity, assuming averaging over multiple realizations [13, 14]. As such, the system can be completely characterized by its response to a temporal impulse located at τ_0. The input dispersion maps the light source spectrum along the time domain, in such a way that an averaged linear frequency chirp of slope $1/\ddot{\Phi}_{In}$ is induced along the duration of the dispersed waveform. The pinhole modulation implements temporal filtering of the chirped light at a reference time, selecting in average a narrow portion of the original spectrum, centered at a wavelength $\omega_{\tau 0}$, which is directly proportional to τ_0, i.e. $\omega_{\tau 0} = -\tau_0/\ddot{\Phi}_{In}$. In this way, the predicted time-to-frequency mapping is performed. Considering that the output of the pinhole modulation process is a short pulse, frequency-to-time mapping is subsequently induced on this pulse by the output dispersion [7, 15], with a scaling defined by $\ddot{\Phi}_{Out}$. These combined processes lead to the anticipated impulse re-location at $M\tau_0$, where $M = -\ddot{\Phi}_{Out}/\ddot{\Phi}_{In}$ defines then the temporal magnification factor of the imaging system.

For an incoherent temporal imaging system with an optimum temporal pinhole, the system response can be mathematically described as

$$\left\langle I_{Out}\left(\tau\right)\right\rangle \propto I_{In}\left(\frac{\tau}{M}\right)\otimes I_{Pinhole}\left(\frac{\ddot{\Phi}_{In}}{\ddot{\Phi}_{In}+\ddot{\Phi}_{Out}}\tau\right), \quad (1)$$

where we recall that $M = -\ddot{\Phi}_{Out}/\ddot{\Phi}_{In}$ is the temporal magnification factor, $I_{In}(\tau)$, $I_{Pinhole}(\tau)$ and $I_{Out}(\tau)$ are the intensity temporal profiles of the input waveform, temporal pinhole and output waveform, respectively, $\langle . \rangle$ denotes averaging over multiple realizations, and $\otimes$ represents convolution.

In a practical setup, the uniform (infinite-bandwidth) energy spectrum of the ideal white-noise light source is emulated over a limited frequency bandwidth. This imposes a restriction on the system temporal aperture:

$$T_A = 2\pi\left|\ddot{\Phi}_{in}\right|\Delta f_{Opt}, \quad (2)$$

where Δf_{Opt} is the full-width optical bandwidth of the incoherent light source [2].

3. EXPERIMENTS

Fig. 2(a) shows an experimental setup and some results for incoherent-light temporal magnification [9]. Broadband incoherent light with a nearly uniform spectrum [~11.6 nm bandwidth and centered at a wavelength of 1549.9 nm, see Fig. 2(b)] is firstly generated by spectrally filtering the optical radiation from a superluminescent diode followed by amplification with a semiconductor optical amplifier. The input incoherent optical signal to be imaged is obtained by intensity modulation of the incoherent light with the RF waveform under analysis using a 40-GHz electro-optic intensity modulator. The RF waveform is generated by a 12-GHz electronic arbitrary waveform generator and then amplified by a 12-GHz electronic amplifier. Fig. 2(d) shows an example of input temporal waveform, which is a periodic two-pulse sequence of Gaussian-like pulses. The two different consecutive pulses have FWHM of 196 ps and 110 ps, respectively, and their time separation is 1.17 ns. The modulated light is sent through the input dispersive line (dispersion = –692 ps/nm), and the time-domain pinhole, which is realized by another 40-GHz electro-optic intensity modulator driven by an electronic pulsed waveform generated by the same arbitrary waveform generator, subsequently amplified by a 12.5-GHz electronic amplifier. Fig. 2(c) shows the measured temporal pinhole, which has a nearly rectangular shape with an intensity FWHM of ~146 ps. After the temporal pinhole, the light is sent through the output dispersive line (dispersion = 1981 ps/nm), and it is subsequently measured with a 45-GHz photo-detector attached to a 28-GHz real-time oscilloscope. As shown in Fig. 2(e), the *averaged* output intensity waveform is a magnified temporal image of the input intensity waveform, with the expected magnification factor of M = 2.86, along the 8-ns (23-ns) input (output) temporal aperture. According to the theoretically expected temporal magnification factor, the intensity FWHM of the shortest pulse in the output temporal waveform, namely the imaged version of the shortest input pulse, should be $\Delta T_{Out} = |M|\Delta T_{In} = 2.86 \times 110 \text{ ps} \approx 315 \text{ ps}$. In the experiment, the measured intensity FWHM of the corresponding pulses in the output temporal waveform is ~345 ps, which, when compared with the ideal value, gives an input temporal resolution of $\delta\tau_{In} \approx \sqrt{345^2 - 315^2}/|M| \text{ ps} \approx 49.2 \text{ ps}$. The input resolution estimated from these measurements is in excellent agreement with the theoretical resolution of ~51 ps, leading to an experimental TBP of 162.6 (8 ns/49.2 ps).

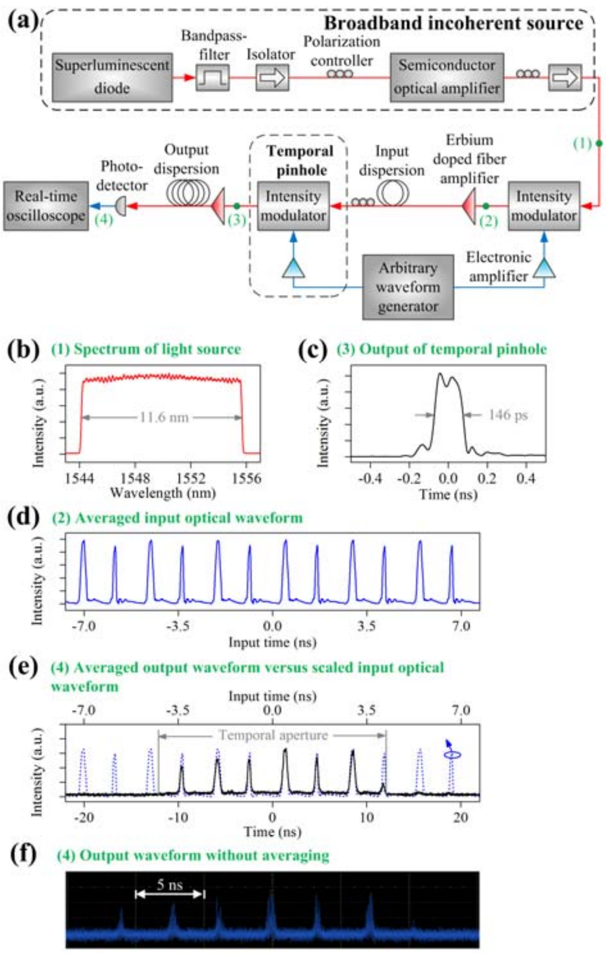

Fig. 2 Experimental setup and output waveforms along an incoherent temporal imaging (magnification) system. (a) Experimental setup. (b) Spectrum of the broadband incoherent light source. (c) Optical output from the temporal pinhole. (d) Input optical temporal waveform. (e) Temporal intensity profile (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 (b)-(e) are averaged for 256 times. (f) Temporal intensity profile of the output image without averaging.

4. CONCLUSION

In summary, we have recently demonstrated novel schemes for temporal imaging of incoherent-light intensity waveforms, avoiding the use of coherent-light processes, e.g. pulsed light sources. Our demonstrated schemes are particularly interesting for detection, measurement or processing of high-speed RF waveforms. More generally, this work could open the path for realization of a wide variety of critical instruments for measurement, generation, cloaking and processing of high-speed electronic, RF or optical signals in a very simple and practical fashion, by exploiting the ample wealth of knowledge developed for coherent temporal imaging and related platforms.

5. REFERENCES

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