Time reversal of optical waves

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ABSTRACT

Wave propagation is a linear process in the time domain in the absence of loss. This property has been exploited over the past 20 years for wave control through highly disordered media. Let’s consider a short pulse propagating through a disordered system. If the field associated to the pulse is recorded and played backwards, the wave is focused back to the source at a single delay. This time reversal control has been evidenced for low frequency waves such as acoustics, water waves and microwaves. Over the last decade, partial spatiotemporal control of optical waves has been demonstrated by means of spatial light modulators. However full optical time reversal remains elusive. In this paper, we demonstrate time reversal of optical waves with a device that can manipulate independently amplitude and phase of 90 spatial and polarization modes, over 4 THz of bandwidth and 20 ps of delay. For the first time we demonstrate arbitrary control of all the degrees of freedom: spatial (amplitude and phase), polarization, spectral and temporal after propagation through a multimode fiber. This new ability to control and manipulate at will optical waves opens promising opportunities for linear and nonlinear optical phenomena, such as imaging and optical communications.

Keywords: Spatial light modulator, Pulse shaping, Phase conjugation, Spectral holography, Time Reversal, Spatiotemporal control, Multimode Fiber

Time reversal experiments exploit the linearity of wave propagation in time to spatially and temporally refocus a wave back to the source. Time reversal originally started with acoustics waves [1], and has been extended to low frequency waves. Over the last decade, wavefront shaping of optical waves through scattering medium have shown partial spatiotemporal control of light [2], but the full control of all the degrees of freedom has not been evidenced. In this paper, we combine a multi plane light conversion (MPLC) system [3] with a spectral pulse shaper [4] to demonstrate full control of all the degrees of freedom of an optical beam: spatial, polarization, spectral and temporal properties. Arbitrary vector fields can thus be generated through free space, an optical multimode fiber or even a scattering material. This new device could find applications in all fields that require full spatiotemporal field control, such as imaging with the delivery of optical pulses, or mode division multiplexing for optical communications.

The experimental system is shown in Fig.1. Light propagates from a single-mode fiber (SMF) into a multi-port polarization resolved spectral pulse shaper. The output ports consist of a 1D array of 45 Gaussian spots. By programming different phase masks on the spatial light modulator (SLM) inside the pulse shaper, the amplitude and phase of each spectral component in each polarization can be independently manipulated for each output port. The 1D array of Gaussian spots is mapped to a 2D set of Hermite-Gaussian (HG) modes through a MPLC device [5]. This mapping of the two transverse spatial dimensions of the output beam onto a single spatial dimension of the SLM through the MPLC device, enables three output dimensions (2D spatial modes, 1D spectral/temporal) to be independently controlled on the 2D surface of the SLM. As the output ports are HG, the device is compatible with both fiber and free-space and the output beam has no regions of dead-space in both the near and far-fields.

We demonstrate full control of 90 spatial/polarization modes over 4THz of bandwidth between 1535 and 1570nm, and approximately 20ps of delay. The output of the device is couple to 5m of graded-index (OM3) multimode fiber (MMF). We characterize the device and its attached fiber by measuring its optical transfer function (OTF) with swept wavelength digital holography (SWDH): we measure the output spatial fields for each polarization state as a function of wavelength for each of the 90 input spatial/polarization mode that the device can address. Time reversing the OTF enables to generate arbitrary vector fields at the distal end of the fiber. Fig. 2 illustrates full field spatiotemporal control. We conjugate transpose the OTF to calculate the input wavelength-dependent spatial/polarization field required to generate a desired wavelength-dependent vector field at the distal end of the fiber. The input field is generated by programming accordingly the SLM, and the output field is characterized using SWDH. Fig. 2 also shows spatiotemporal control, where arbitrary fields can be created in arbitrary polarizations at arbitrary delays. The desired output is specified in the time...
domain rather than frequency domain. The output field is characterized using SWDH, and its Fourier transform yields the corresponding temporal response.

Figure 1. (a) Simplified and (b) detailed schematic of our optical time reversal device, capable of mapping an input vector spatiotemporal input field onto an arbitrary vector spatiotemporal output field. Amplitude, phase, spatial mode, polarization and spectral/temporal properties can all be independently addressed simultaneously.

Figure 2. Experimental demonstration of spatiotemporal control. (a) Horizontally polarized focus spot in a single position as a function of wavelength (b) “Clock-hand” rotating as a function of delay for the two output polarizations.

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