Waveform Generation in Space, Frequency, Time and Polarization

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Abstract *This paper shows three devices to perform 4D waveform generation: a time reverser device combining a wavelength selective switch and a mode multiplexer, a spectral mode equalizer that comprising a wavelength blocker and a mode multiplexer, and a mode beamformer comprising an array of modulators and a mode multiplexer.*

Introduction

Optical pulses were first shaped into complex waveforms using the spectral pulse shaper[2]. Femtosecond features could be accessed via static phase and amplitude masks placed at the focus of a spectrometer. These pulse shapers produces fs features and enabled experiments such as quantum coherent control of atomic systems[3]. These spectral pulse shapers eventually evolved into telecom friendly devices known as wavelength selective switches[4] (WSS) which places a steering mirror at the spectrally dispersed focal plane to steer different wavelengths back to separate fibers. Inside the focal plane of a WSS, both (two) spatial dimensions are used to handle steering and wavelength. These devices were recently adapted to handle spatial modes, but not to arbitrarily shape them.

In parallel, shaping the spatial profile of beams[5],[6] is found in space-division multiplexed communications[7], endoscopy[8], and astronomy (e.g., adaptive optics). These techniques typically involve projecting a beam onto a spatial light modulator, applying a spatial phase and amplitude modulation, and then focusing (i.e., Fourier transforming) this shaped beam through a scattering medium or into an optical fiber. Here, two spatial dimensions are used to handle the both transverse dimensions. Since there are only two polarizations, they can normally be handled on two separate locations on the spatial light modulator. The drawback to these devices is they cannot arbitrarily specify the mode profile on a wavelength-by-wavelength basis.

Obviously, combining spectral, spatial, and polarization pulse shaping in one device is challenging as there are only two spatial dimensions to modulate. We will show two solutions for controlling all degrees of freedom of light in this paper by combining spatial light shapers and spectral shapers. In addition, we will preview our progress on optical beamforming, an alternative method of 4D control, where we use an array of high speed coherent transmitters coupled to a mode multiplexer.

Time Reverser Device

Follow figure 1 for a description of the time reverser device[1]. It is called a time reverser due to its similarities to acoustic time reversal[9]. The basic procedure to perform acoustic time reversal is: 1) place an array of microphones around the edge of a tank, 2) cause a disturbance in the middle, 3) record these waves, 4) replace microphones with speakers, 4) replay the recorded waves backwards in time, 5) watch these waves focus at the center of the tank. This is much harder to accomplish in optics because the frequencies are much higher, therefore it is much easy to accomplish time reversal with a spectral and spatial optical pulse shaper rather than modulation.

The time reverser combines a multiplane light conversion[11],[12] (MPLC) mode multiplexer with a wavelength selective switch. The MPLC device converts the 2D spatial profile of Hermite-Gaussian modes into a 1D array of spatially separated Gaussian beams. At each wavelength, a single input beam into the WSS can be arbitrary split in amplitude and phase to the array of 1D beams. These beams are then transformed into their respective spatial modes while maintaining

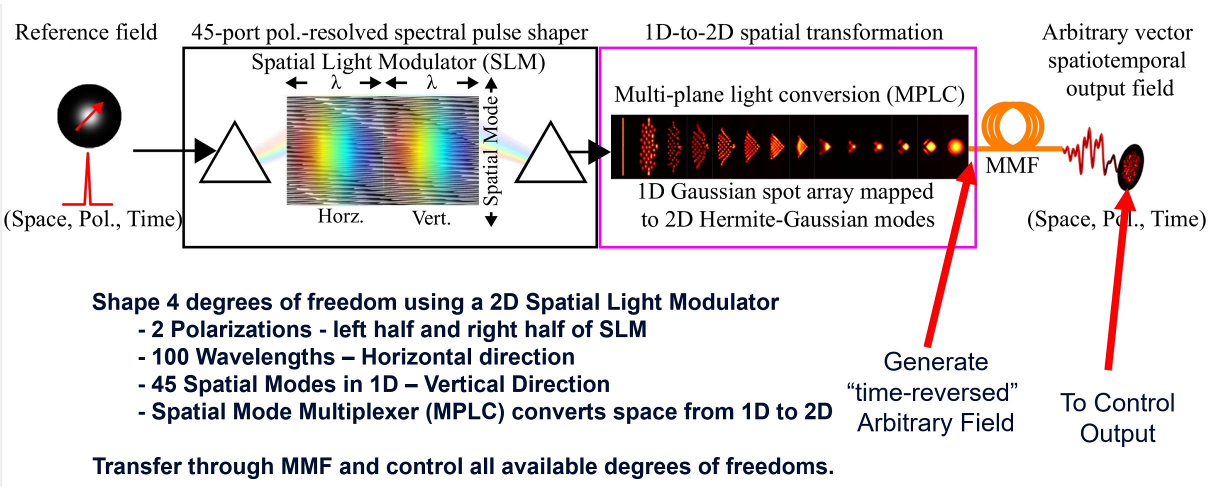

Fig. 1: Time reverser device[1].

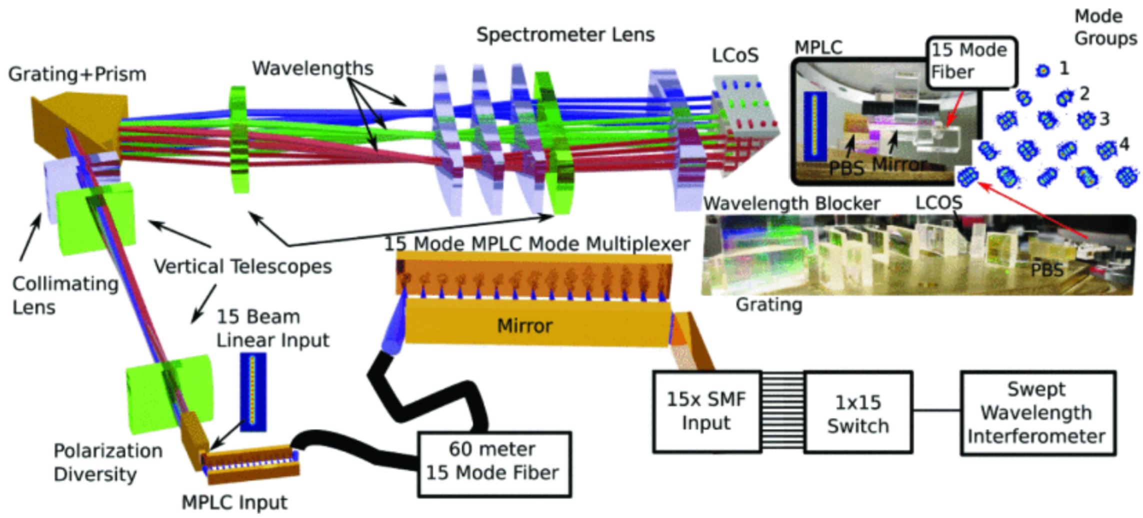

Fig. 2: Wavelength blocker[10].

their amplitude and phase. The super position of these modes creates a unique spatial profile.

Each wavelength input into the device can have a unique spatial amplitude and phase profile. If a short optical pulse is input into the time reverser, each of its spectral components can be shaped and maintain their phase relationships producing complex temporal waveforms that change their spatial profile with sub ps resoltion spanning 50ps. Note, polarization is handled on the left and right halfs of the spatial light modulator. Numerous examples of shaped waveforms can be found in the paper[1].

Spectral and Spatial Wavelength Mode Equalizer

Figure 2 describes the mode wavelength blocker presented last year[10]. In contrast to the time reverser which was a single input, multiple output device, the spectral and spatial wavelength mode equalizer is a multiple input, multiple output device that provides independent modulation to each mode. The input and output of this device is a single 15 mode fiber. This device places a MPLC at the input of a wavelength blocker to demultiplex the modes into an array of spots. Each demultiplexed mode is spectrally dispersed across a separate section of the LCoS spatial light modulator where its amplitude and phase can be arbitrarily and independently programmed. For those familiar with transfer matrices, this device only manipulates the diagonal of the transfer matrix, or N matrix elements rather than the full $N \times N$ required for optical multiple input multiple output processing. Future devices will eventually implement a full spectral and spatial modal cross connect.

Progress Towards Optical Beam Forming with 45+ Modes

Figure 3 shows our experimental testbed to demonstrate (in the future) optical beamforming.

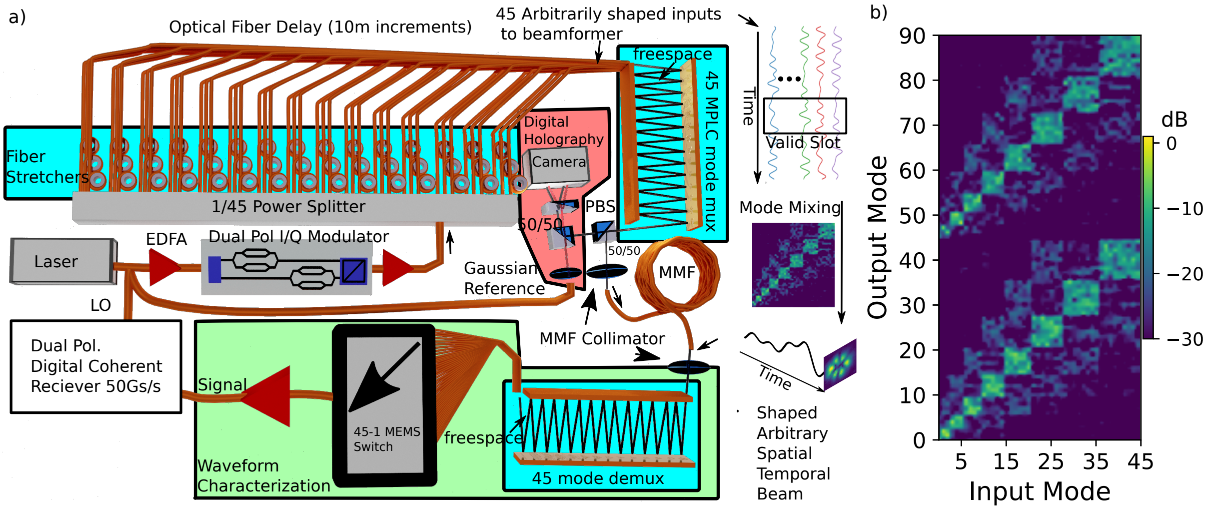

Fig. 3: Progress towards 45+ mode beam forming (a) Experimental setup. A Hz level linewidth laser is modulated and fed to a 1x45 splitter. Each splitter arm is connected via fiber delays with 10 m relative increments to 45 piezo-based stretchers for phase stabilization. The 45 output fibers are then connected to the inputs of a 45-mode multi-plane light conversion mode-multiplexer. A beamsplitter is inserted at the MUX output, prior to collimation, to tap of a part of the output bean. This signal is combined with a flat-phase reference beam in an off-axis digital holography configuration to extract the relative phase of each mode, which is acting as error signal for updating the piezo stretchers. The output is either spliced directly to the receiver demultiplexer or to a 4.5 km multi-mode fiber span. The outputs of the receiver demultiplexer are connected via an optical switch to a real-time oscilloscope. (b) Transfer matrix (single input pol) of the transmitter multiplexer showing an integrated cross-talk of $<$-9dB and mode-dependent loss of 3.6 dB.

It is called beamforming because the intent is to produce any spatial/spectral field at the output of a long multimode fiber. Such examples of formed beams could be focusing to a single spot, scanning a beam, producing a short pulse in space and time, and projecting images. The previous two devices use a passive device to shape the optical field and the temporal domain was controlled via shaping the optical spectrum. The optical beamformer uses an array of modulators input to a spatial mode multiplexer to accomplish 4D shaping using only 2 spatial dimensions. The spectrum is shaped via time domain modulations. The mode multiplexer converts these temporal modulations at separate spatial locations into overlapping spatial modes. The main advantage with this device is it can produce infinitely long shaped waveforms, whereas the drawback or challenge with this device is the optical bandwidth is narrow because it is directly proportional to the electrical bandwidth. The primary challenge with the fiber optic testbed is obtaining enough high speed devices and phase stabilizing paths. Rather than building an integrated circuit with 90 modulators and obtaining 90 high speed DACs and drivers, we adopted a time multiplexing scheme to emulate 90 independent signals using a single dual pol I/Q modulator and fiber delays. Because of some long fiber delays (400m) we are using a Hz level laser source and fiber stretchers to stabilize the phase of the many paths[13].

Conclusions

Hope you enjoyed reading this paper! Spectral, spatial and temporal shaping require complex devices to fully control all degrees of freedom of the optical field.

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