Gain and Temporal Equalizer for Multi-Mode Systems

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Abstract: We present a device enabling individual spectro-temporal control of 15 spatial modes. Realizing independent control over both polarizations on each mode, flexible attenuation and ±20ps of tunable delay over bandwidths exceeding 100 nm is enabled.

1. Introduction

Optical control of all of lights degrees of freedoms, space, polarization, wavelength, and time, is challenging. Spatial mode multiplexers and reconfigurable liquid crystal on silicon (LCoS) based mode devices can shape the spatial property of modes [1,2]. Wavelength selective switches (WSS) [7], optical pulse shapers, and wavelength blockers [8] can control the spectral amplitude and phase which allows full control of the temporal impulse response and spectral shape. However, there are few demonstrations of devices that attempt to control both the spatial properties and the spectral properties simultaneously.

In this work, we build a spatial mode temporal equalizer that combines functionality of a mode multiplexer/demultiplexer and an array of 30 1×1 wavelength selective switches (i.e., wavelength blockers or spectral pulse shapers) in a single device. By controlling the holograms applied to the spectrum of each spatial mode, the delay and loss of each spectral component of each demultiplexed mode is arbitrarily set. The device can provide upwards of 20 ps delay programmable between 1510 nm and 1620 nm. To demonstrate the devices functionality in a communications scenario, we connect it to 60-m of 15-mode graded index multimode fiber [5] and reduce the differential group delay of the span from 25-ps to less than 10-ps. The demonstrated prototype provides an important step towards

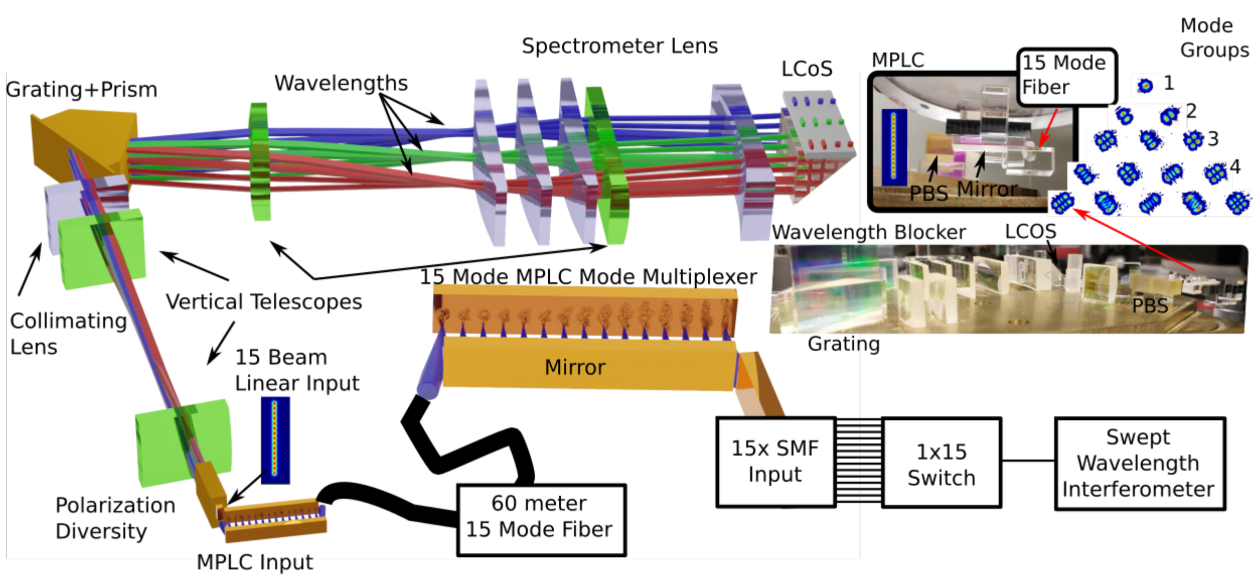

Fig. 1: Gain and Temporal Equalizer for 15 spatial modes comprising a multiplane light conversion mode multiplexer to feed a 30 port wavelength blocker with an array of demultiplexed modes. The equalizer is connected to 60 meters of 15-mode fiber and demultiplexed/multiplexed onto 15 single mode fibers using a second MPLC device for characterization of its transfer matrix using a swept wavelength interferometer.

enabling multi-mode components and systems, such as amplifiers and transmission links, with low MDL and DMD.

2. Device Design and Measurement Setup

A diagram of the proposed device is shown in Fig. 1. It consists of two main parts: a mode-multiplexer based on multi-plane light conversion (MPLC) [3,4] performing mode to space conversion and a liquid crystal on silicon (LCoS)-based spectral pulse-shaper. The input fiber was graded-index multi-mode fiber (GI-MMF) supporting 15 spatial modes on two polarizations [6]. The MPLC functionality is to convert the spatial modes from the GI-MMF that cannot be interfaced with a free space switching device into a phase stable liner array of demultiplexed Gaussian beams. It was implemented in a folded structure using reflective phase masks and a dielectric mirror. The MPLC comprises 15 phase masks spaced at 1-mm with a 8-mm of free space propagation between each phase mask. The MPLC provides a one to one mapping between an array of linear spots with 30µm beam waist and 127 µm pitch and the Hermite-Gaussian (HG) mode patterns shown in the Mode Groups inset in Fig. 1.

The output linear array of spots is interfaced directly with a 30 port pulse shaper section to allow the spectro-temporal response of each mode and polarization to be individually controlled. The pulse shaper, which is similar to a wavelength blocker or gain equalizer, itself consisted of a polarization splitting section, and cylindrical optics to separate port steering functionality (green lenses) from wavelength functionality (blue lenses). In the vertical direction, a front telescope magnifies the vertical direction by 2 to exactly fit 30 ports onto the 1080 pixel LCoS display. The 1 to 1 vertical telescope in the spectrometer relays the beams from the grating onto the LCoS. In the wavelength, the beams expand and are collimated onto the 1201 line/mm transmission grating which is bonded to a prism to enable operation between 1450-nm and 1650-nm. After the grating 4 lenses act as a single Fourier lens to focus each spectral component to a different spatial location. The polarization diversity used 20mm YVO_4 to vertically offset the input 15 beams by 2mm. The blocker optics were cemented using UV epoxy to a base and then directly coupled to the linear array side of a 15-mode MPLC mode multiplexer which is held upside down. Direct coupling of the two systems reduces the loss and device footprint (MPLC input in Fig. 1 is to scale) by avoiding the need for additional imaging optics.

Prior to assembly, the multi-port pulse shaper was characterized using a swept wavelength interferometer (SWI) system and the MPLC was characterized using digital holography. The laser used covered 110 nm bandwidth, from 1510 to 1620 nm with variable sweep up to 2000 nm/s. The SWI system used multiple delay lines to enable coherent measurements of all ports in each scan [9].

The combined device was characterized in reflection mode with one mode at a time. Cross-terms are hence neglected and each delay is instead measured with respect to a fixed reference point. Worth emphasizing here is that this arrangement using a circulator is not limited to the characterization setup. By connecting a circulator to the multi-mode input of the MUX inside the device. However, here the MUX was connected via a 60m graded-index MMF fiber segment to a second 15-mode MPLC-based MUX to enable excitation of all modes. The input fiber array was connected to a switch to enable selective excitation of each mode. The MMF fiber segment was used to scramble the modes and induce additional measurable DGD. Prior to splicing the fiber between the two MUXes, the delay spread was measured using SWI. While the modes within each group are strongly coupled as therefore stays together over the short piece of fiber, a delay spread of about 20 ps was observed between different mode-groups.

3. Results

Before assembly MUX and the multi-port pulse shaper were individually characterized to determine the respective sub-system performance. The multi-port shaper was first characterized to determine the position of each beam on the LCoS and correction factors for hologram generation was determined. The result of a beam scan is shown in Fig. 2(a). We observe that the beams spans the full range of the LCoS display, with small gaps on the edges and in the middle. In the current design delay compensation is implemented by saw-tooth beam steering holograms in the horizontal direction which will add loss as delay is increased. Figure. 2(b) shows the additional loss associated with a certain delay averaged over all ports as a function of frequency. A delay of about ± 10 ps can be applied to each port while operating within 3 dB added loss. ± 15 ps delay imparts an acceptable additional loss of 4 dB. The insertion loss was about 4.5 dB for the best 7 ports and below 7.5 dB for all ports. The edge ports had slightly higher loss following the tight coupling margin at the pulse shaper input.

The MUX was measured using digital holography, enabling full complex transfer matrix measurements without requiring a MUX-DEMUX pair. The resulting transfer matrix for one of the two MUXes used is shown in Fig. 2(c). As can be seen, the coupling is tightly confined within each mode group. The coupling within each group originates in the short piece of fiber (about 2m) from the MUX collimator to the camera. The average cross-talk was below -17 dB

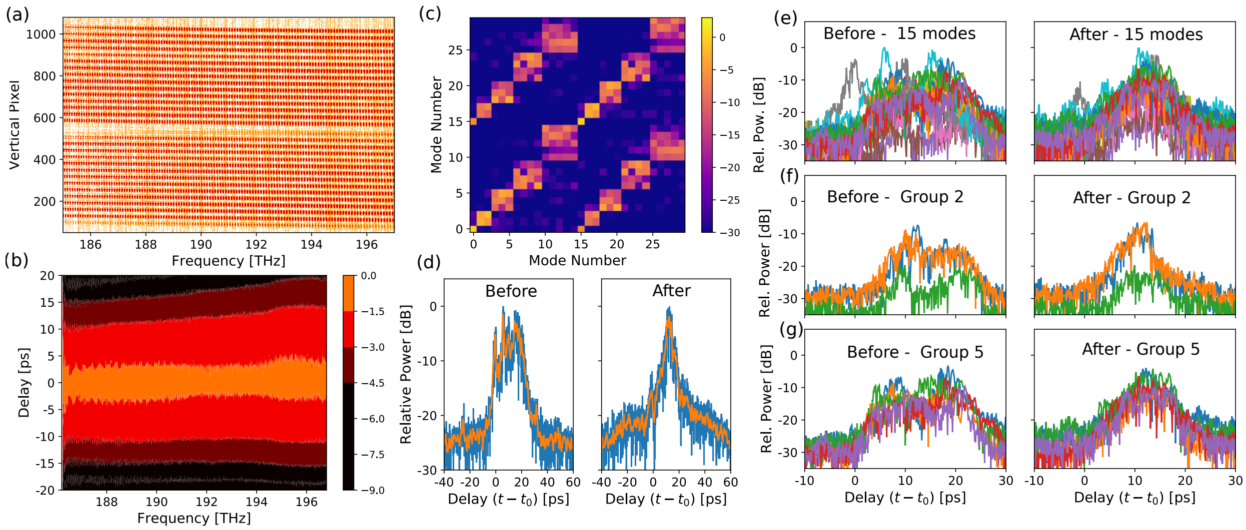

Fig. 2: (a) Measured port locations over the 1920×1080 LCoS display. (b) Measured delay versus additional loss induced from steering. (c) Measured 30×30 transfer matrix of the 15 stages multiplane light propagation mode multiplexer (2×2 blocks are input/output polarization and the 5 small blocks are the mode groups). (d) Summed temporal trace from measuring each mode through the system in reflection mode using the SWI before adjusting the delay of the mode groups and after aligning all mode groups. (e) Before an after delay compensation for each individual input mode (sum is shown in (d)). (f,g) Before and after delay compensation of the 3 inputs corresponding to mode group 3 and 5, respectively.

and the measured MDL was about 5.5 dB at the center wavelength of about 1550 nm.

The performance of the assembled prototype device can be seen in Fig. 2(d). The traces show the averaged impulse response for all 15 input/output modes. Before performing delay compensation, the width of the impulse response (-5dB) exceeds 20 ps. The orange trace shows the data filtered with a 10 point moving average filter, displaying a spiky behaviour with multiple peaks present representing different mode groups across the 110-nm measurement range. After delay compensation, the response is reduced to < 10 ps.

Fig. 2(e) show the individual impulse responses of the 15-modes prior to averaging. Fig. 2(d,e) shows only the impulse responses of mode group 2 and mode group 5, as shown in Fig. 2(f-g). The results indicate that we can compensate the delay of each spatial mode across 110-nm bandwidth. Note, the losses of the complete device with MPLC approach 17-dB due to two passes through the MPLC.

4. Conclusions

We have demonstrated a spectral pulse shaper for multi-mode systems supporting up to 15 spatial modes that is capable of independently control and shape the field of each mode in a multi-mode beam. The device is based on direct coupling of a 15-mode multiplexer based on multi-plane light conversion to a multi-port pulse shaper. It can adjust the delay within ± 20 ps for each mode-group arbitrarily across 110-nm bandwidth, and has full control over both polarizations. We believe that devices like the one presented can play a key roll in the development of future multi-mode systems and components by enabling tunability previously only available to single mode systems.

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