Spectral Shaping In a Multimode Fiber By All-Fiber Modulation
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We experimentally demonstrate spectral shaping in a multimode fiber by macro-bend based transmission matrix engineering. We implemented an all-fiber reconfigurable narrowband single- and dual-window bandpass filters. © 2022 The Author(s)

1. Introduction

In recent years multimode optical fibers (MMFs) are at the focus of numerous studies aiming at enhancing the capacity of optical communication and endoscopic imaging systems [1,2]. Since multiple transverse modes of the fiber are interrupted by inter-modal interference and coupling, along with modal dispersion, the information delivered by the fiber is scrambled. To fully utilize the potential of MMFs, it is desired to have coherent control over the spectral and spatial degrees of freedom of the light transferred by the fiber. One of the promising approaches for unscrambling the transmitted information is shaping the optical wavefront at the proximal end of the fiber to get a desired output at its distal end [3]. Typically, in wavefront shaping the incident wavefront is controlled using spatial light modulators (SLMs), digital micromirror devices (DMDs) or nonlinear crystals. These approaches, however, require free-space propagation of the incident light.

Recently, we implemented control of the light that propagates inside the fiber by effectively manipulating the transmission matrix (TM) of the fiber [4]. Our method relies on applying controlled weak local macro bends along the fiber. The bends change the fiber’s TM by changing the local propagation constants of the guided modes and by inducing mode coupling. Using this approach, we have demonstrated the ability to shape the desired spatial field at its distal end and to transmit images through a strongly perturbed MMF [5].

In this work, we expand our all-fiber wavefront shaping approach to the spectral domain. We implement a reconfigurable spectral filter by controlling the TM of a multimode fiber. Using a 1m-long fiber we demonstrate a tunable bandpass filter with a full-width-half-maximum (FWHM) of 260 pm. Using the same setup, we also implement a dual-window bandpass filter. The spectral resolution of the filter is determined by the bandwidth of the fiber which in turn depends on its length and its numerical aperture (NA). Hence, to narrow down the bandwidth of the filter, we replace the 1m-long MMF by a 15m-long fiber and achieve a bandpass filter with a FWHM of 30 pm.

![Fig 1: Experimental setup for an all-fiber spectral shaping in a multimode fiber.](image)

(a) Configuration I - light from a broadband LED is coupled to a single mode fiber (SMF). The light is then coupled to a multimode fiber (MMF), which is spliced to another SMF, that is coupled to a spectrometer. (b) To manipulate the transmission matrix (TM) of the fiber, we place 28 computer-controlled piezoelectric actuators along the fiber. Each actuator can travel ~1mm in the vertical direction, pressing the fiber from above. The actuators create local deformations that change its propagating constants and induce mode mixing. (c) The optimization algorithm (simulated annealing) searches for the optimal travel of each actuator, that maximizes the transmission in a desired spectral or spatial window. (d) Configuration II – to improve the FWHM of the filter. Light from a fiber-coupled laser with a tunable wavelength at telecom band, is coupled to an MMF and detected by an InGaAs camera imaging at its distal end.

2. Methods

The experimental setup is depicted in Figure 1a. A broadband fiber-coupled LED source is coupled to a 1m-long step-index MMF, with an NA of 0.22 and a core diameter of 50 μm. The input and output facets of the MMF are
spliced to single mode fibers (SMF). The spectrum of the light in the output of the SMF is determined by the complex wavelength-dependent interference of the fiber modes at the splicing point. We manipulate this interference using an array of computer-controlled piezoelectric actuators that apply local bends at multiple positions along the fiber (Figure 1b). To obtain a desired spectrum at the distal end of the SMF, we use the simulated annealing optimization algorithm to find the optimal configuration of the actuators, i.e. the optimal travel of each actuator [6].

While the FWHM of the fiber is determined by the fiber length, it is also limited by the spectral resolution of the measurement devices used in the optimization process, which is limited in configuration I to 35 pm. In order to implement bandpass filters with FWHM of less than 35 pm, we used a tunable laser source at telecom wavelengths with a spectral resolution of 10 pm and an InGaAs camera, instead of the broadband LED and spectrometer. The camera captures the spatial interference pattern from the distal end of the MF. We fixed the laser at a specific wavelength and enhanced the intensity at a chosen region of interest on the camera, whose area is smaller than the area of a speckle grain, using the same optimization process described above. Finally, we swept the wavelength of the laser around the optimization wavelength and measured the wavelength dependent intensity at the chosen region of interest.

3. Results and Discussion

To demonstrate a tunable bandpass filter, we used the LED and spectrometer configuration (configuration I) to maximize the output intensity of the transmission in a chosen spectral band, each time for a different central wavelength (Figure 2a). We achieve peak-to-background ratios of 15 to 20 with a FWHM of 260 pm. The efficiency of the system, defined by the ratio of the output and input intensities at the chosen spectral band, is 0.06. To demonstrate the versatility of the spectral shaping, we also implement a dual window bandpass filter, with two peaks separated by 1.5 nm and a FWHM of 250 pm for each peak (Figure 2a). We further managed to improve the FWHM of the bandpass filter by employing a 15m-long fiber and the tunable laser configuration (configuration II, see Figure 2b). This way, the FWHM we were able to achieve is 30 pm with a peak-to-background ratios of 10-12.

While here we used a camera imaging the distal end of the fiber to select one spatial channel, one can simplify the detection method by replacing the camera with a SMF that is spliced at the distal end of the MMF along with a telecom photodiode. To improve the performance of the all-fiber modulation, namely to obtain higher peak-to-background ratios and a higher versatility, more actuators can be used [4]. To further improve our spectral resolution, longer multimode fibers can be used. For example, we anticipate that with a 100m-long fiber one could obtain bandpass filters with a spectral resolution of 1pm at telecom wavelengths [7].

![Fig 2](image_url)

Fig 2: (a) Experimental transmission spectra of our all-fiber tunable band-pass filter. Each curve represents the average of 6 spectra that were optimized to maximize the peak-to-background ratio at the desired wavelength. Different curves correspond to bandpass filters centered at different wavelengths. The inset represents the transmission optimized for a dual window filter. (b) The transmission spectrum from configuration II of a 1m long MMF (blue) and a 15m long MMF (red), the FWHM of the red curve is 30pm. All spectra are normalized by the average background. All error bars correspond to the standard deviation of the different optimization runs.

4. References

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