Spatial-Spectral Holographic Mode Demultiplexing, Dispersion Compensation, and Routing

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***Abstract*—Mode group demultiplexing, modal dispersion compensation, and header-based modal-channel self routing in multimode fiber networks is enabled using an all-optical signal processing technique based on spatial-spectral holography in order to achieve transparent all-optical networks.**

***Index Terms*—spatial-spectral holography, multi-mode fibers, modal dispersion, optical signal processing**

I. Introduction

The unique properties of photons (noninteracting in free space, massive parallelism, high resolution encoding in space and angle, ultra-wide bandwidth, nonlinear interaction in materials, etc) are harnessed by optical signal processors in order to process information for special purpose applications. Both linear analog signal and image processing techniques, as well as nonlinear photonic logic approaches have been pursued, and have achieved varying levels of success and competitiveness. [1] Just as neuro-computing is best suited for pattern recognition applications and quantum computing finds its competitive niche for factoring using Shor's algorithm, optical processing remains the most competitive when the arriving information is already coherently encoded in the optical domain. Wideband wavelength-multiplexed, fiber-optic communication is the dominant technique for long-haul communication, and the optical switching and routing of these signals is currently a fruitful application area for many optical signal processing techniques and advanced optical device technologies. Recently, multi-mode fibers (MMF) have emerged as the next horizon of ultra-high capacity optical communication, enabled by the development of practical on-chip, multichannel, wideband, coherent-detection technologies as well as sufficient front-end real-time on-chip adaptive signal processing to combine and dispersion compensate a handful of multiplexed channels emerging from these fibers. [2] To separate the different communication channels injected into such a MMF the fiber output speckle field must be separated onto an array of small detectors each the size of an individual speckle, interferometrically combined with a stable reference for coherent detection, and then processed with an array of multiple-input multiple-output (MIMO), adaptive tapped-delay line (TDL) correlation-based processors. However, this task requires multichnnel detection and analog-to-digital conversion at such a high bandwidth the dynamic range is low and an enormous signal processing throughput that inevitably will out pace even the most optimistic projections for the capabilities of conventional digital computing approaches as the number of channels and bandwidth increases. The wideband and spatially complex speckle fields emerging from such a multi-mode fiber present a nearly ideal opportunity for a special-purpose all-optical computing front-end signal processor.

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II. Modal demultiplexing using SSH

In this paper we will show how wideband and multi-wavelength information can be encoded on orthogonal superpositions of the different spatial modes of a multi-mode fiber [3], [4] and then unscrambled and dispersion compensated using spatial-spectral holography (SSH). [5], [6] Previous analog optical approaches to modal multiplexing (MMux) made broadband communication via MMux appear unfeasible because of the complexity of launching individual modes, [7] the inevitable coupling of modes due to perturbations, [8] the mode dependent loss, the enormous modal dispersion, [9] and the difficulty of separating out the superposition of modes at the multi-mode fiber output. Restricted mode excitation has been used to increase multi-mode fiber bandwidth-length products, and angular multiplexing has allowed the transmission of a few annular modes [10] or even holographically isolated single modes [11] over a few meters. Holographic modal separation techniques utilize field orthogonality at the fiber input and anywhere along the length of the fiber due to the unitarity of the modal propagation, and are therefore capable of separating individual inputs that are launched initially as orthogonal modal superpositions inputs such as input spots, not just sinle modes, by making use of holographic recording of the output speckle fields in a volume hologram. [3] In this paper these holographic, spatial modal multiplexing ideas are extended to simultaneously account for the spectral dependence of the speckle, [12] performing dispersion compensation and simultaneous modal unscrambling by using SSH.

Our approach allows multiplexing of $10^2 - 10^3$ signals (a small fraction of the 10^4 modes in a typical 100μm-core step-index multi-mode fiber). SSH processing enables a potential capacity of a single fiber approaching a Petabits/sec using 50 wavelength channels of 40 GHz bandwidth (or 500000 wavelength channels of 4GHz bandwidth) and 500 spatial mode groups. Such an enormous capacity is sufficient for every household in the US to have many Mbit/s of

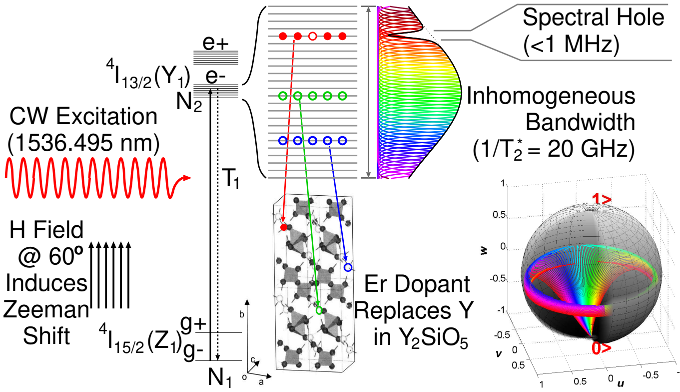

Fig. 1. Spectral hole burning in Er^{3+}:YSO operates at 1536nm. With a 1T applied magnetic field a narrow linewidth laser can burn a sub-MHz wide spectral hole by exciting from a ground state to an inhomogeneously broadened band 25GHz wide. The dynamics of each homogeneous sub-band can be illustrated on the Bloch sphere.

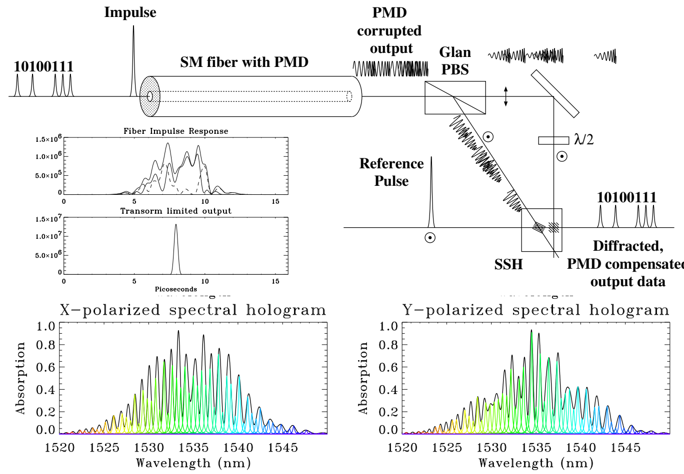

Fig. 2. PMD Compensation by splitting the two polarization components, rotating one to the same polarization, cohering holographically in a SSH by interfering with a reference impulse. The insets show the simulated PMD spectra at the fiber output, the two recorded spectral gratings, and readout by a data packet.

bandwidth devoted to them on every multi-mode fiber using a specific wavelength/mode address. Using SSH for linear adaptive modal exchange allows mode re-use and enables more efficient network topologies without the difficult requirement for nonlinear wavelength conversion currently envisioned for WDM networks.

Spatial-spectral holography (SSH) allows us to compensate for all orders of dispersion, mode coupling, and polarization mode dispersion (PMD) in MMF in order to achieve wide bandwidth in each spatially multiplexed modal channel to enable ultra-high capacity optical communication through modal multiplexing. The capacity for hundreds of spatially multiplexed channels in just one multi-mode fiber will enable petabit per second (PBPS) aggregate bandwidth capabilities in a single fiber. The extremely high spectral resolution of SSH materials also enables ultra-dense WDM in which individual users can inject and extract spectral channels of arbitrary width down to the MHz range into selected modal channels (without being limited by the speckled fiber outputs as are conventional spectral channelizers). And finally, we show opportunities for all-optical switching and transparent routing using the adaptive capabilities of spatial-spectral holograms to convert between modal addresses, to switch signals from one multi-mode fiber to another, and to use the spatial-spectral (SS) holographic grating persistence to enable all-optical header-based self-routed circuit-switched protocols.

A. *Spatial-Spectral Holography*

When two modulated beams intersect in a cryogenically-cooled inhomogeneously broadened absorber, they interfere in both the spatial and spectral domains to produce a grating that can both spatially diffract and temporally delay a subsequent Bragg-matched readout beam to produce a photon echo. The structure of Er^{3+}:YSO and excitation on the Bloch sphere. is illustrated in Fig. 1 when in the presence of an appropriate magnetic field. When co-doped with Eu the Erbium absorption line is broadened to a 25GHz bandwidth. A CW laser can burn a narrow spectral hole in the inhomogeneous absoption band, while a pair of short pulses can excite a periodic spectral grating that produces a time delayed photon echo of any subsequent input within the grating lifetime. Spectral resolutions can be below a MHz in cryogenically-cooled crystals and bandwidths can be as large as 250GHz with a persistence time of 10ms. [13] These capabilities have been suggested for OCDMA routing, [14] and here we extend those ideas to header self-routing and multi-mode dispersion compensation by recording dispersed frequency-varying speckle fields emerging from MMF as spatial-temporal impulse responses.

B. *PMD compensating using spatial-spectral holograms*

Polarization mode dispersion (PMD) compensation using SSH (shown in Fig. 2) is based on splitting the output into two orthogonal components, rotating one by 90° with a half wave plate, angularly combining, and then treating this as 2 input modes, each of which will be Bragg matched to a different recorded spatial-spectral grating. These modes are cohered by interfering both of them with a collimated Gaussian beam reference pulse. Due to PMD the amplitude distribution and phase of the two modes varies as a function of frequency, and this information is recorded as spectral gratings for the 2 channels, as shown in Fig. 2. The diffraction by the spectral hologram of subsequent data bits split by the PBS and incident on the SS crystal reproduces a transform-limited plane-wave pulse in a single polarization, thereby fully compensating for the effects of PMD to all orders. By using a sufficiently wide-band Erbium-glass or polymer-based SSH material, this single SSH can perform PMD compensation for all WDM channels within the inhomogeneous band in parallel.

C. *Modal dispersion compensating using SSH*

The multi-channel multi-mode fiber dispersion compensation system is shown in Fig. 3. Using one multi-mode fiber, a spatial-spectral hologram is used to record the spatio-temporal impulse response of each communications channel by coupling an impulse (or Broadband spectrally-uniform coded waveform) from each modulator as an independently resolvable beam into the multi-mode fiber and then interfering the speckled and dispersed fiber output with a corresponding

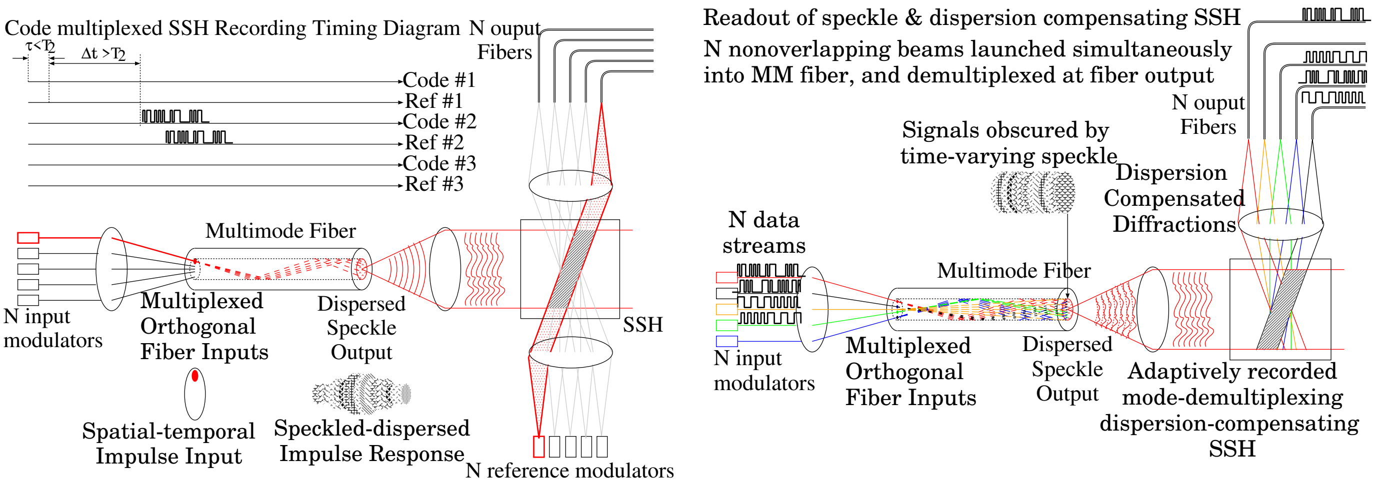

Fig. 3. Multi-channel-multi-mode fiber dispersion compensation system. Right) Sequential recording and Left) readout. To direct a specific MMF input to a desired output destination, the header code for that fiber also illuminates a beam passing through the SSH towards the destination fiber, and cycling through all the inputs to the MMF records the desired, modal demultiplexing, dispersion compensating, and routing SSH. Readout of the data streams of all the inputs to the MMF will occur in parallel throughout the SSH, directing each Bragg-matched diffracted and dispersion compensated data stream towards the desired destination fiber, which can be either a single-mode fiber or another multi-mode fiber.

plane wave reference impulse (or matched code) in the volume of the SSH crystal. Each resolvable input to the multimode fiber remains as a field orthogonal speckled superposition of modes due to the unitary character of optical propagation, even in the presence of mode coupling. The speckled outputs associated with each input record orthogonal holograms within the SSH with the Bragg orthogonal reference waves at each resolvable frequency. Fiber modal dispersion will affect the relative phase of the modes as a function of frequency, and this is encoded into the phase of the grating matched to that mode. The maximum differential time delay must be less than the inverse spectral resolution of the SSH, which is readily achieved by the sub-MHz resolution of a cryogenically-cooled SSH, but such ibroadband multi-GHz microsecond-long tapped-delay-line correlation-convolution processing is very difficult to achieve with any other approach. Then, when data is transmitted through the same modulators and through the multi-mode fiber, the modally scrambled and dispersed speckle field emerging from the fiber is diffracted off the spatial-spectral hologram thereby fully compensating for the fiber modal dispersion and reproducing a plane wave directed to the corresponding output carrying the reconstituted wide-band data stream. Periodically re-exposing the SSH allows tracking of modal phase drifts at a refresh rate up to about 100Hz, sufficient for many fiber environments.

A frequency-dependent 1+1D beam propagation simulation of slab waveguide propagation, SSH hologram recording and readout that demonstrates each of these steps is shown in Fig. 4. To simplify the computational load a 1=!D multimode slab waveguide is used instead of a circular multimode fiber since many wavelengths across the inhomogeneous band must be independently propagated and the fields and holograms stored. Propagation at various different wavelengths through a slab waveguide that has mode coupling turned on after the first quarter is shown in the upper left. The recorded SSH and the readout diffracting off these holograms at each wavelength within the band is shown in the lower left. On the right The output when a short pulse is applied to the slab waveguide at each of 3 input angles illustrating the long tail due to modal dispersion is shown on the right. Finally, the spatio-temporal diffraction from the SSH shows the nearly transform limited re-creation of the impulse demonstrating both spatial modal unscrambling and simultaneous modal dispersion compensation.

D. *Packet self-routing using spatio-spectral holograms*

By using SSH processing a packet destination can be encoded onto a header to record a persistent spatial-spectral routing grating so that a packet will agilely follow the header through the network on a circuit-switched path selected by the choice of header waveform. To record a grating that routes the packet to its destination, the SSH is illuminated by a coherent laser modulated by a delayed version of the same temporal waveform as the header, beam-deflected towards the desired output (either a multimode or even a singlemode fiber). The spatio-spectral interference records a dispersion-compensating, mode-unscrambling, time-delay spatial-spectral (SS) hologram that operates over the full header bandwidth. Subsequent spatio-temporal diffraction of the data payload by this grating gives a transform limited output pulse propagating in the direction of the desired output fiber for every bit launched into the multi-mode fiber. Each destination is associated with its own header code and different packet headers would not form a strong correlation time-delay grating and thus would only very weakly diffract a dispersed and temporally smeared echo towards the wrong destination. A stack of such SSH gratings in a single SSH crystal can accommodate scores of such input and output multimode fibers, each carrying 100s of modal-multiplexed channels with 100s to 1000s of wavelength channels each.

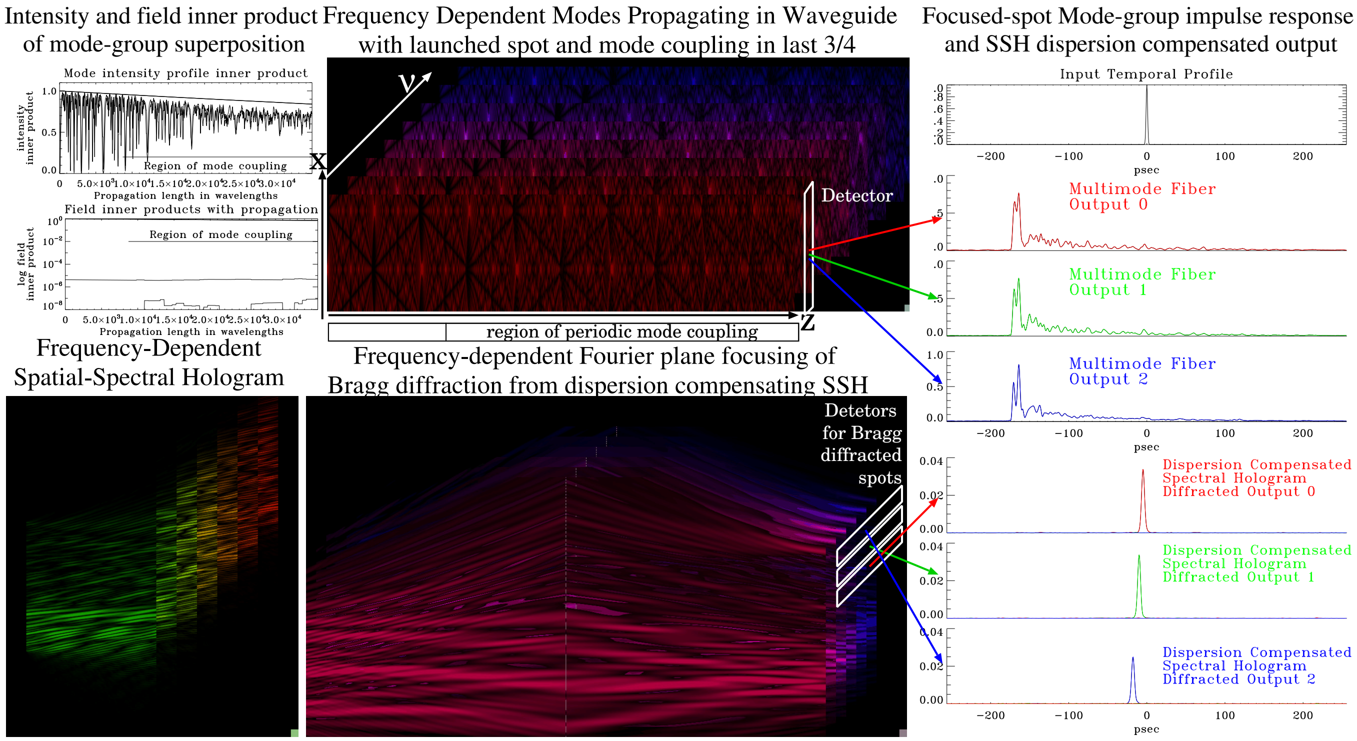

Fig. 4. Frequency depenndent beam-propagation simulation demonstrating all the key steps of SSH dispersion compensation illustrated for the case of a 1-D step-index slab waveguide. A broadbandwidth short-pulse focused spot is launched into the slab waveguide which has modal coupling turned on after the first 1/4, and the output temporal profiles seen by a large area detector have long extended tails. Bragg-matched SS holograms are recorded at the waveguide output using 3 angle-multiplexed plane wave impulses. Upon readout, each frequency-dependent Bragg-diffracted beam is focused onto a photodetector, reproducing a dispersion compensated output impulse for each spatially-multiplexed launched bit, demonstrating the capabilities for multi-mode dispersion compensation and arbitrary mode-group demultiplexing.

III. Summary and Outlook

Spatial-spectral holographic materials provide a novel approach to multimode fiber-optic signal processing enabling modal de-multiplexing and wide-band dispersion compensation for the first time. The efficiencies of existing SSH materials needs to be increased, for example by either using gain media instead of absorption holograms [15] or by combing SSH diffraction with a separate multimode gain stage. [16] The bandwidth of current Erbium-based SSH crystals isuch as Er^{3+}:$LiNbO_3$ extends to about 250GHz in the fiber telecom band, and this would need to be increased to the range of a few THz (to match the full Erbium amplifier gain band) as has been demonstrated at the expense of spectral resolution by using rare-earth doped glasses instead of crystals. With these enhancements SSH processing could potentially increase the bandwidth capabilities of multimode fibers and enable a new type of transparent all-optically routed fiber network.

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