Title

Review of Experimental Methods of Optical Modulation and Polarization Maintenance

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Abstract: Investigation into the methods for optical amplitude and polarization modulation and the tools necessary to maintain these modulations for effective experimental use.

INTRODUCTION

In "Integrated structured light architectures" by Lemons, Randy, et al, the authors outline a method whereby, after splitting a laser into eight beamlines, they modulate characteristics of seven of the eight individual light beams like phase ($\Delta\phi_i$), amplitude (A_i), polarization state ($\wp_i$), and timing (Δt_i) before recombining the beam into a single laser pulse.[1] This process allows the researchers to produce light with desired "spatio-temporal" characteristics since the combination of the modulated beamlines creates a single beam with intensity, phase, and polarization dependent on both position (near-field versus far-field) and time.[1]

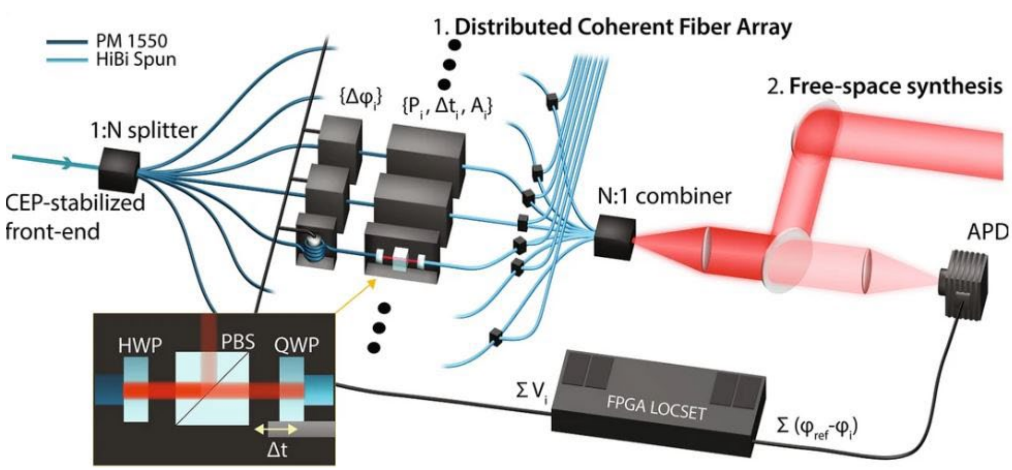

Figure 1. Experimental Setup Utilized in "Integrated structured light architectures"[1]

Modulating characteristics like phase, amplitude, polarization state, and timing allows the authors to encode information into the individual beamlines; when combined into a single laser pulse with multiple beams, this encoded information lends opportunities for use in fields like optical communications and quantum computation.[1] Projects in quantum computation face the issue, however, where these characteristics need dynamic modulation.[1] As evidenced in Figure 1, each individual aspect requires independent tools for successful modification; for example, phase modulation alone requires the use of both a field programmable gate-array (denoted in Figure 1 as FPGA LOCSET) to provide a reference phase from the one beamline left unmodulated and a piezoelectric transducer-based fiber stretcher (referenced in the above figure as $\{\Delta\varphi_i\}$) to modify phase with respect to the reference.[1]

Amplitude modulation characterizes changes in the magnitude of the optical field, and as such, the intensity of the light since intensity is proportional to the magnitude squared.[2] In the paper, the researchers achieve amplitude modulation using erbium-doped fiber amplifiers (EFDA).[1] These fibers commonly operate at wavelengths greater than 1.5 µm, as reflected in the paper where the researchers utilized light centered at 1.55 µm with a spectral bandwidth of 14.9 nm.[3,1] EDFAs powerfully modulate the amplitude of light with these amplifiers offering gains of up to 25 dB.[3] Like with any material, light photons excite ions to higher energy levels.[4] For erbium-doped fiber, this constitutes laser diodes exciting the erbium ions to either the $^4I_{13/2}$ energy level or $^4I_{11/2}$ energy level (however, for this experiment, the ions likely were pumped to the $^4I_{13/2}$ energy level since the $^4I_{11/2}$ level usually constitutes pumping at a wavelength of around 980 nm).[5] Then, stimulated emission brings these ions back to the $^4I_{15/2}$ energy level.[5] This process of emission results in more energy due to the ion emitting a photon equivalent in energy to the bandgap between its transition.[4]

In contrast, the EDFAs cannot modulate the polarization of light: a process facilitated using a polarizing beam splitter in the paper (denoted as PBS in Figure 1).[1] As described in both the methods and illustrated in figure 1, the beam splitter split the light into two orthogonal beamlines; typical beam splitters take unpolarized light and separate the beams into two normal, polarized beams via polarization splitting.[1,6] In polarization splitting, the beams of light are linearly polarized with either "p-polarization," referring to an orientation along the axis parallel to incidence, or "s-polarization," referring to an orientation orthogonal to the axis of incidence.[18] The paper ultimately mentions that the light exhibits circular polarization, which suggests the use of a quarter wave plate (denoted by QWP in Figure 1).[7] A quarter wave-plate modulates linear polarization to circular polarization since it hinders one of the electric field components by a quarter wavelength, thus polarizing the optical wave at 45 degrees. [7]

After achieving the desired modulation, one important step in the above research's methods made use of SPUN-HiBi fibers (denoted by the lighter blue-colored fibers in Figure 1) in order to maintain the circular polarization of the individual beamlines before ultimately synthesizing the beams.[1] SPUN-HiBi, by definition, are "highly birefringent," hence their name.[8] At first, it seems counterintuitive to use fibers with any birefringence to maintain polarization; birefringence describes a material where, taking the two polarized, orthogonal modes of a light beam, the modes move through the medium with different propagation constants.[9] If the researchers solely aim to maintain the polarization of the light they transmit, then a naïve solution would insist on the use of fibers with no birefringence, or a circularly symmetric wire where both modes see equal propagation constants.

The primary issue with that unsophisticated solution undercuts the fact that the absence of birefringence in fibers proves an unattainable ideal.[10] A combination of the impossibility to manufacture a perfectly symmetric medium, and the fact that birefringence emerges as spatially dependent due to factors like "bend, twist, and anisotropic stress"[10] and temporally dependent due to temperature.[10] As such, any waveguide that maintains a light beam's given polarization needs to also couple that challenge with the issue of a material's inherent birefringence. The solution to this problem constitutes creating fibers with a very high-level of birefringence such that one axis has a much higher index of refraction in order to reduce mode coupling. [10] With reduced mode coupling, then light remains primarily along the same polarized mode, a fact reflected in the equation for the beat length of a fiber:[10]

$$L_b = \frac{2\pi}{\beta_x - \beta_y}$$

Beat length L_b represents how well a fiber maintains the polarization of light since physically, it gives the distance along the fiber until the two fundamental modes develop a phase difference of 2π. [10] The greater the difference in the principal indices of refraction, then the smaller the length of wire required to maintain the circular polarization of the light before ultimately collecting the beamlines and collimating them using the N:1 combiner illustrated in Figure 1.[1]

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