

Polarization Conjugation without Optical Nonlinearity

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Abstract—We demonstrate optical polarization conjugation using a simple architecture that combines self-configuring Mach-Zehnder interferometers and a polarization splitting grating coupler. This allows the removal of polarization perturbations in an optical system, such as birefringence in a fiber, using linear components and operations. Conjugation is shown for a fiber system with a polarization extinction ratio better than -28 dB.

Index Terms—PIC, Optical polarization, Optical phase conjugation

I. INTRODUCTION

Conventional phase conjugation enables the removal of spatial distortions to a beam propagating backward through some distorting optics, recreating the original beam at the source, but typically requires nonlinear optics and external pump lasers [1]. Likewise, full vector phase conjugation is possible, including the conjugation of polarization, with specific nonlinear interactions [2]. In both cases, high efficiency conjugation is a significant challenge, and existing schemes lack practical implementations. Many problems associated with polarization in optical systems could be addressed by polarization conjugation, such as the effective removal of polarization variability in conventional optical fibers. Here, we show how polarization conjugation can be achieved in a simple, practical system without using non-linear optics or external lasers.

II. METHODS

A. Device Architecture

Our device, shown in Fig. 1a, features a polarization splitting grating coupler (PSGC) that separates orthogonal polarization components of a beam and couples them to waveguides comprising a binary tree of Mach-Zehnder interferometers

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(MZIs) [3]. Each MZI is composed of a 50:50 beam splitter, an internal phase shifter (θ) to adjust the splitting ratio, a 50:50 beam combiner, and an external phase shifter (ϕ) to adjust the relative phase between the arms of the MZI. The output of a polarization-distorting system is coupled to the PSGC; then, the phase shifters are sequentially adjusted in a self-configuration process [4], [5] to maximize coupling out of a single port. This both characterizes the polarization state [3] and sets the MZIs to remove polarization variations from the system for a beam propagating in the reverse direction.

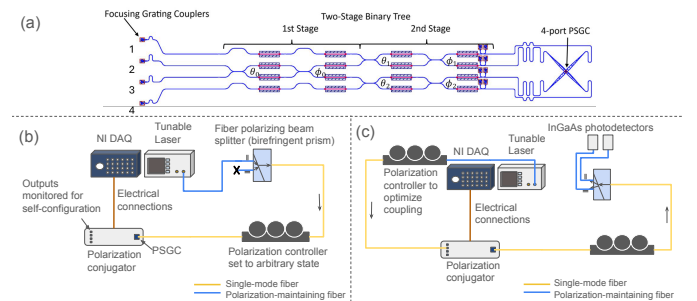


Fig. 1. (a) Schematic of polarization conjugator. Setup to (b) compensate polarization effects by self-configuration and (c) for conjugate generation and extinction ratio measurement.

We used standard single-mode fiber in a Thorlabs FPC562 manual polarization controller to alter the polarization state of our input. We set the input to a particular linear polarization using a fiber-based polarizing beam splitter (PBS) (Thorlabs PBC1550SM-APC). After configuring the phase shifters, the conjugator was operated in the reverse direction by coupling to a single grating coupler and collecting the output light from the PSGC. Perfect polarization conjugation results in an identical state to the original input emerging backwards at the input, after propagating through the fiber. So, here, the polarization extinction ratio (PER) was measured at the input with reference to the original polarization and calculated as the

ratio of intensities between the component linearly polarized in the orientation of the input, $I_{||}$, and the component linearly polarized in the orthogonal orientation, $I_{\perp}$, as separated by the PBS.

$$PER = 10 \log_{10} \left(\frac{I_{||}}{I_{\perp}} \right) \quad (1)$$

B. Polarization Conjugation

Polarization conjugation can be described by decomposing an electric field vector into real x and y amplitudes with some relative delay ϕ_0 between the two components as shown in (2). This constitutes the input vector to the system, $|\psi_{fwd}\rangle$.

$$|\psi_{fwd}\rangle \equiv \begin{bmatrix} E_x \\ E_y \end{bmatrix} \equiv \begin{bmatrix} E_{x0} \\ E_{y0} e^{i\phi_0} \end{bmatrix} \quad (2)$$

The optical system, represented by complex 2x2 Jones matrix U_{os} , will impart some transformation on the input, scrambling the polarization state. The polarization conjugator, represented by complex 2x2 matrix U_{MZI} , must apply a transformation to this new vector to negate the effects of the optical system. Between the optical system and MZIs, our device converts the input vector from a polarization basis in one spatial mode to two quasi-TE waveguide modes. By self-configuring the MZIs for a given polarization state, the power is combined to emerge entirely from one waveguide arm, enforcing the output, $|\psi_{MZIout}\rangle$, as defined in (3).

$$U_{MZI} U_{os} |\psi_{fwd}\rangle \equiv |\psi_{MZIout}\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (3)$$

Once properly configured, we perform the conjugation by sending light in the reverse direction through the optimized MZI arm. Assuming a unitary optical system, the transpose operator is used to describe this reverse operation [6]. We can then relate the amplitude emerging at the original input, $|\psi_{back}\rangle$, to the backward input vector, $|\psi_{MZIin}\rangle$. This backward input is set to $|\psi_{MZIout}\rangle$ from the self-configuration process. Taking the complex conjugate of all terms yields (4).

$$|\psi_{back}\rangle^* = (U_{MZI} U_{os})^\dagger |\psi_{MZIin}\rangle^* \quad (4)$$

Since our input, $|\psi_{MZIin}\rangle$, is real, (4) can be written as

$$|\psi_{back}\rangle^* = (U_{MZI} U_{os})^\dagger (U_{MZI} U_{os}) |\psi_{fwd}\rangle. \quad (5)$$

Because our system is unitary, $(U_{MZI} U_{os})^\dagger (U_{MZI} U_{os})$ is simply the identity matrix, yielding

$$|\psi_{back}\rangle = |\psi_{fwd}\rangle^* \quad (6)$$

Thus, the polarization emerging from the PSGC in reverse operation will be the polarization conjugate of the vector transformed by the optical system.

III. RESULTS

Fig. 1 shows the measured PER for a set of arbitrary paddle orientations on the polarization controller and represented on Poincaré sphere as the polarization state measured at the PSGC. The conjugated beam exhibited an extinction ratio between -28.0 dB and -32.7 dB for all orientations, confirming compensation can be achieved for a general system. The PER was also evaluated at wavelengths between 1500 nm – 1580 nm. The device performs optimally between 1530 nm – 1550 nm, corresponding to the limitations of the PSGC [3].

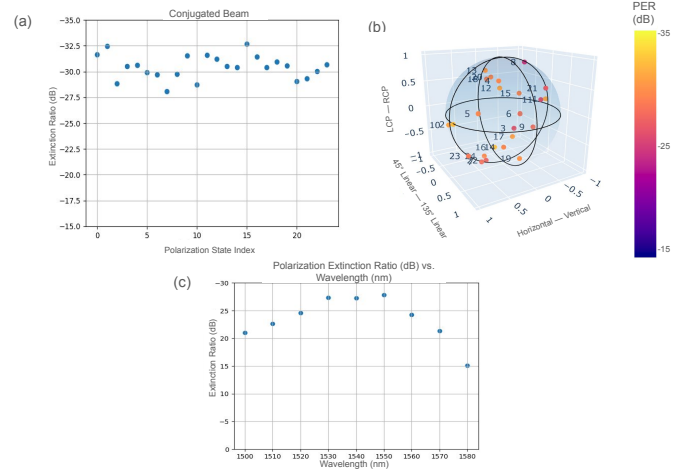


Fig. 2. (a) PER of conjugated beam for 24 arbitrary fiber configurations and (b) represented by polarization state on the Poincaré sphere. (c) PER for an arbitrary paddle orientation from 1500 nm - 1580 nm.

IV. CONCLUSION

We have shown a practical approach to polarization conjugation using a silicon photonic platform. The architecture, demonstrated using birefringence in an optical fiber, can compensate for unwanted polarization effects in optical systems. The approach can be modified for high-speed operation and continuous compensation of polarization variations in a system using integrated photodiodes and faster actuators, such as microelectromechanical phase shifters or electro-optic materials.

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REFERENCES

- [1] R. W. Boyd, *Nonlinear Optics*. Academic Press, 1992.
- [2] R. P. M. Green, S. Camacho-Lopez, and M. J. Damzen, "Experimental investigation of vector phase conjugation in Nd3+:YAG," *Opt. Lett.*, vol. 21, no. 16, pp. 1214–1216, Aug. 1996, doi: 10.1364/OL.21.001214.
- [3] C.G. Valdez, A.J. Miller, A.R. Kroo, C. Roques-Carnes, D.A.B. Miller, and O. Solgaard, "Integrated photonic polarization synthesizer and analyzer," *Light Sci Appl.*, in press.
- [4] D. A. B. Miller, "Self-aligning universal beam coupler," *Opt. Express*, vol. 21, no. 5, pp. 6360–6370, Mar. 2013, doi: 10.1364/OE.21.006360.
- [5] D. A. B. Miller, "Self-configuring universal linear optical component," *Photon. Res.*, vol. 1, no. 1, pp. 1–15, Jun. 2013, doi: 10.1364/PRJ.1.000001.
- [6] D. A. B. Miller, "Analyzing and generating multimode optical fields using self-configuring networks," *Optica*, vol. 7, no. 7, pp. 794–801, Jul. 2020, doi: 10.1364/OPTICA.391592.