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Nonlinear control of structured light

Structured light, where complex optical fields are engineered across all degrees of freedom, has recently become a highly topical area of research. This rise is fueled by the development of sophisticated toolkits for the creation, control, and detection of light. Traditionally, both the creation and detection of structured light have assumed a fixed wavelength, relying on linear superpositions of light patterns. In this work, we introduce a nonlinear approach to control structured light, enabling the transfer and retrieval of information independent of wavelength, all while preserving the light's spatial structure. This is achieved by integrating digital holography with nonlinear optics, demanding precise spatial overlap of interacting beams within the nonlinear medium. To meet this challenge, we developed a light-by-light alignment technique within the nonlinear crystal, enhancing frequency conversion fidelity to beyond 90%. This enabled the design of custom light patterns tailored to specific signals, improving the frequency conversion efficiency of structured light by more than 40%. While frequency conversion enables pattern creation across a range of wavelengths, high-fidelity detection is essential to extract the encoded information. We address this by introducing a nonlinear version of modal decomposition, allowing us to unravel information in the near-infrared using a basis encoded in the visible wavelength. With full control over both the creation and detection of structured light, we further deployed our system in a prepare-and-measure configuration over a highly aberrated optical channel. Remarkably, the phase conjugation inherent to the nonlinear process allowed us to naturally correct for distortions at the speed of light, without the need for active measurements. We believe that our nonlinear framework for structured light unlocks powerful new capabilities, paving the way for future breakthroughs in optical communication, imaging, and spectroscopy.

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