Bessel-Beam-Generating Integrated Optical Phased Arrays

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Abstract: Generation of Bessel beams using integrated optical phased arrays is proposed and experimentally demonstrated for the first time. A quasi-Bessel beam with a ~14 mm Bessel length and ~30 µm FWHM is generated using a splitter-tree-based architecture.

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1. Introduction to Bessel Beams and Integrated Optical Phased Arrays

Due to their unique properties [1], Bessel beams, and their Bessel-Gauss experimentally approximations, have contributed to a variety of important applications and advances, including reduction of scattering in microscopy [2] and adaptive optical communications [3]. Conventionally, Bessel beams have been generated using a bulk optics approach wherein an Axicon lens (a conical glass prism) is illuminated with a truncated-Gaussian beam to produce a Bessel-Gauss beam at the output [1]. Moreover, recent work has turned towards generation of Bessel beams in more compact form factors, including Dammann gratings [4] and meta-surfaces [5]. However, these demonstrations do not provide full on-chip integration and most are fundamentally limited to static beam formation.

Integrated optical phased arrays, which manipulate and dynamically steer light [6], provide one possible approach to generation of quasi-Bessel beams in a fully-integrated platform. However, current phased array demonstrations have focused on systems which steer beams or project arbitrary radiation patterns in the far field [6, 7]. Near-field manipulation has only recently been explored for holography [8] and focusing applications [9]. In this work [10], integrated optical phased arrays are proposed and demonstrated for the first time as a method for generating quasi-Bessel beams in a fully-integrated, compact-form-factor system with natural scaling to an active demonstration.

2. Bessel-Beam Phased Array Theory

A phased array is a system comprised of an array of antennas that are fed with controlled phases and amplitudes to generate arbitrary radiation patterns. If the antennas are spaced with a uniform pitch and fed with a linear phase and a Gaussian amplitude distribution (as shown in Fig. 1a), the array generates a steerable, diffracting Gaussian beam in the far field of the array. In contrast, if an "Axicon-like" element phase distribution is applied in addition to the Gaussian amplitude, the array will generate a quasi-Bessel beam in the near field of the array, as simulated in Fig. 1c. This Gaussian element amplitude distribution and Axicon phase are given by

$$A_n = \exp\left(\frac{-4\ln(2)(n-N/2-1/2)^2}{(NA_0)^2}\right) \qquad \Phi_n = \Phi_0 \frac{-|n-N/2-1/2|+N/2-1/2}{N/2-1}$$

where A_n and Φ_n are the amplitude and phase applied to the nth antenna, A_0 and Φ_0 are the variable amplitude and phase parameters, and N is the total number of antennas in the array. Similarly to a Fresnel lens, Φ_n can be encoded modulo 2π, as shown in Fig. 1b.

For potential applications, two valuable figures of merit of a quasi-Bessel-beam-generating array are the power full-width half-maximum (FWHM) of the central radiated beam and the Bessel length. Similarly to bulk implementations, these variables depend on the aperture size of the array and the maximum variation of the Axicon phase, Φ_0. For example, for a 64 antenna array with 10 µm antenna pitch, 1550 nm wavelength, $\Phi_0 = 5\pi$, and $A_0 = \sqrt{2}/2$, the simulated FWHM and Bessel length are found to be 30.7 µm and 11.4 mm, respectively.

3. System Architecture, Implementation, and Experimental Data

As a proof of concept, a passive quasi-1D Bessel-Gauss-beam-generating phased array is designed and fabricated in a CMOS-compatible foundry process at CNSE SUNY using a silicon-nitride splitter-tree architecture as shown in Fig. 1d. A 6-layer multi-mode interference (MMI) splitter tree is used to evenly distribute the input power to 64 waveguide arms with a final pitch of 10 µm [7]. On each arm, a tap coupler and a phase taper are placed to enable static

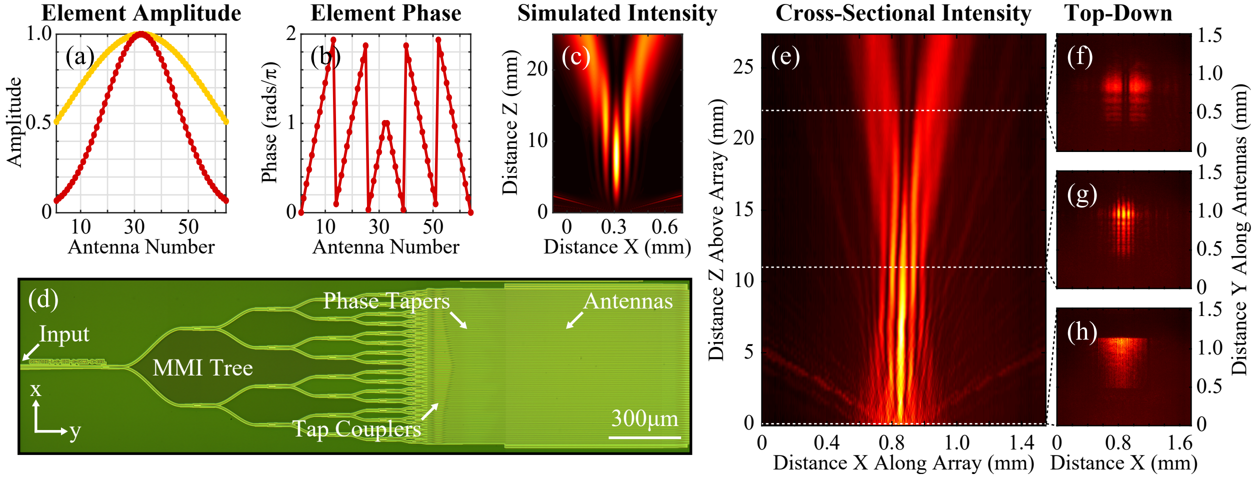

Fig. 1. (a) Element amplitude distribution for a Gaussian-amplitude phased array with $A_0 = 1/2$ (red) and $A_0 = 1$ (yellow). (b) Element phase distribution for a quasi-Bessel-beam-generating array with $\Phi_0 = 5\pi$. (c) Simulated array-factor intensity above the array for a quasi-Bessel array with $A_0 = 1/2$ and $\Phi_0 = 5\pi$. (d) Micrograph of the fabricated quasi-Bessel phased array. (e) Measured cross-sectional intensity (in dB) above the fabricated array with top-down intensity shown (h) in the plane of the chip ($z = 0\,\text{mm}$), (g) within the Bessel region of the radiated beam ($z = 11\,\text{mm}$), and (f) after breakdown of the Bessel region ($z = 22\,\text{mm}$). Element distributions and intensities are shown for an array with 64 antennas, 10 µm antenna pitch, and 1550 nm wavelength.

arbitrary amplitude and phase encoding for each antenna in the array. The coupler and taper lengths are chosen such that a Gaussian amplitude distribution with $A_0 = \sqrt{2}/2$ and an Axicon phase distribution with $\Phi_0 = 5\pi$ are encoded. Finally, a 650-µm-long grating-based antenna [7] is placed on each arm to create a 0.64 mm × 0.65 mm aperture.

To characterize the fabricated array, an optical system is used to image the plane of the chip onto an InGaAs IR camera. The system height is then progressively scanned such that top-down views of the intensity at varying heights above the chip are recorded. The resulting cross-sectional intensity as a function of the distance above the chip and three top-down views are shown in Fig. 1e–h. In the plane of the chip (Fig. 1h), the aperture is illuminated by the antennas. As the system scans through the Bessel region of the beam (Fig. 1g), a characteristic 1D Bessel-Gauss beam is observed with a central-beam FWHM of ∼30 µm along the ∼14 mm Bessel length. Finally, above the Bessel length (Fig. 1f), the central beam is destroyed, the Bessel breaks down, and the light begins diffracting outwards.

4. Conclusions, Anticipated Applications, and Future Outlook

This work presents the first proposal and demonstration of integrated optical phased arrays which generate quasi-Bessel beams in the near field of the array. An arbitrary phase- and amplitude-controlled splitter-tree-based architecture has been developed and used to experimentally demonstrate a quasi-Bessel-beam-generating array with a ∼14 mm Bessel length and ∼30 µm power FWHM. Due to the elongated properties of Bessel-Gauss beams, this on-chip system has important applications, ranging from multi-particle trapping to scalable laser lithography [1–3]. Since the array is fabricated in a CMOS-compatible platform, it is naturally scalable to an electronically-steerable integrated system [6].

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