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Ultra-Dense Waveguide Arrays for Photonic Integrated Circuit

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Abstract *We present two half-wavelength pitched ultra-dense waveguide arrays based on artificial gauge fields (AGF). The AGF-modulated straight waveguide array exhibits an over -35 dB crosstalk suppression for the center wavelength and the bent one shows over 100 nm bandwidth for crosstalk lower than -20 dB. ©2022 The Author(s)*

Introduction

Waveguide arrays are among the fundamental building blocks for integrated photonics. A dense waveguide array could enable high-density integration of waveguide elements, significantly reducing on-chip estate and cost, which usually occupy the largest on-chip area and hamper further improvements of integration-density. As a device, it is also crucial in space-division multiplexing [1], optical phased array, optical interconnection [2, 3], and wavelength-division multiplexers [4, 5].

Reducing the waveguide separations will result in a crosstalk boost that hinders the independent control of signal in a waveguide. Many designs, including plasmonic waveguides [6], inverse design [7], anisotropic metamaterial cladding [8], asymmetrical nano-waveguide [9], waveguide super-lattice [10], and bent waveguides [11] can significantly suppress the crosstalk and miniaturize devices.

Recently, AGF-assisted light-guiding has been proposed and demonstrated [12-14], opening a new door for exploring on-chip light guiding, coupling, and routing.

In this paper, we design and experimentally demonstrate an AGF-based low-crosstalk, half-wavelength pitched dense waveguide array on the standard 220 nm silicon-on-insulator (SOI) platform. The AGF-induced exceptional coupling is observed with a crosstalk of ~-35dB at the wavelength of 1520 nm. Furthermore, we also demonstrate a 64-channel half-wavelength pitched bent ultra-dense waveguide array, which could suppress the crosstalk to lower than -20 dB with a bandwidth of 100 nm. Our approach enables significant on-chip estate reduction, leading to high density photonic integrated circuit, and may open up opportunities for important device performance improvement for half-wavelength pitch OPA and ultra-dense space-division multiplexing.

Principle

Waveguide arrays with AGF, which could be realized by shape-modulation, possess significantly different crosstalk characteristics compared with a similar array without AGF. The shape-modulation introduces an additional phase that modifies the interaction between adjacent waveguides.

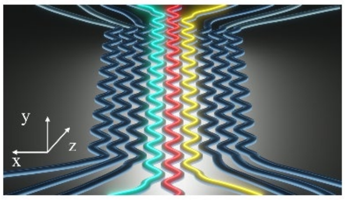

Fig. 1: Schematic of the shape-modulated waveguide array.

For a waveguide array with a sinusoidal (period: P) shape-modulation, i.e., $x(z) = A\sin(\Omega z)$, we have Eq. (1) for β_{peq} (equivalent propagation constant of the system):

$$\beta_{peq} = \beta_0 + \kappa_0 + 2\cos(k_x d)\,\kappa_{eq} \quad (1)$$

Where β_0 is the propagation constant, k_x is the momentum of the Bloch state, d is the pitch of the waveguide array, and κ_0 is the self-coupling coefficient. $\kappa_{eq} = J_0(k_0 n_s A\Omega d)\kappa = J_0(a)\kappa$ is the equivalent coupling coefficient, where k_0 is the momentum of a photon in vacuum, n_s is the refractive index of the substrate, κ is the coupling

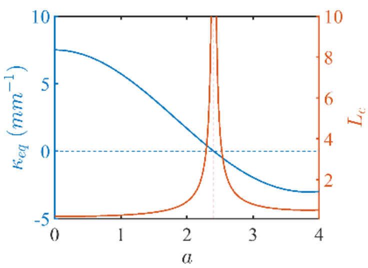

Fig. 2: κ_{eq} and L_c variations as a function of a.

coefficient of a uniform straight waveguide array without AGF, and $J_0(a)$ represents the 0th Bessel function.

Fig. 2 shows κ_{eq} and L_c as a function of a, where $L_c = \frac{\pi}{2|\kappa_{eq}|}$ is the equivalent coupling length. It could be found that $L_c \to +\infty$ when $a \to 2.405$ (the red dashed line), which is the first zero point of the 0th Bessel function. By designing a waveguide array around this point, we can achieve low crosstalk of a densely packed array.

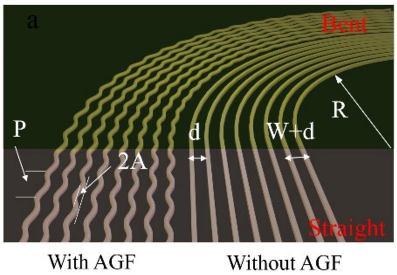

Fig. 3: Schematic of straight and bent dense waveguide arrays with/without AGF.

Design

Based on the analysis above, we design two dense waveguide arrays, straight and bent, with schematic shown in Fig. 3.

For sinusoidal modulated waveguide array, the exceptional coupling is achieved when $a \approx 2.405$. The amplitude of modulation, A, becomes:

$$A = \frac{a}{k_0 n_s \Omega d} \approx \frac{2.405}{k_0 n_s \Omega d} \tag{2}$$

Straight dense waveguide array

The straight dense waveguide array is designed on an SOI platform with the waveguide width and height of 500 nm and 220 nm, respectively. The gap between two adjacent waveguides is 250 nm, corresponding to d=750 nm, to guarantee that $d \le \frac{\lambda}{2}$ for the whole spectrum range from 1500 nm to 1600 nm. The P is fixed at $10\,\mu m$ to minimize the bending-induced extra propagation loss, and the total propagation distance is set to 100 μm.

The light field evolutions of the different waveguide arrays are shown in Fig. 4a. Compared with the conventional waveguide array (upper panel), the light propagating in the sinusoidal waveguide array (low panel) is well confined in the middle waveguide with negligible coupling to adjacent waveguides. Fig. 4b shows the simulated transmission and crosstalk of the sinusoidal-shape-modulated straight waveguide array, showing a negligible insertion loss and a bandwidth of 70 nm for crosstalk lower than -20 dB.

The microscope and SEM images are shown in Fig. 4c. Fig. 4d shows the measured transmission and the nearest neighbor crosstalk with the same structure as Fig. 4b. A significant crosstalk suppression is observed at the wavelength around 1520 nm, which indicates the $\kappa_{eq} \to 0$ and the $L_c \to +\infty$. The crosstalk near the wavelength is about -35 dB and the bandwidth for -20 dB crosstalk bandwidth of about 40 nm.

Bent dense waveguide array

We also apply the shape-modulation to a large scale densely-packed bent waveguide array. The bent waveguide array consists of 64 waveguides with a pitch of 750 nm. Due to the bending induced propagation constant deviation, we replace the constant amplitude of the shape-

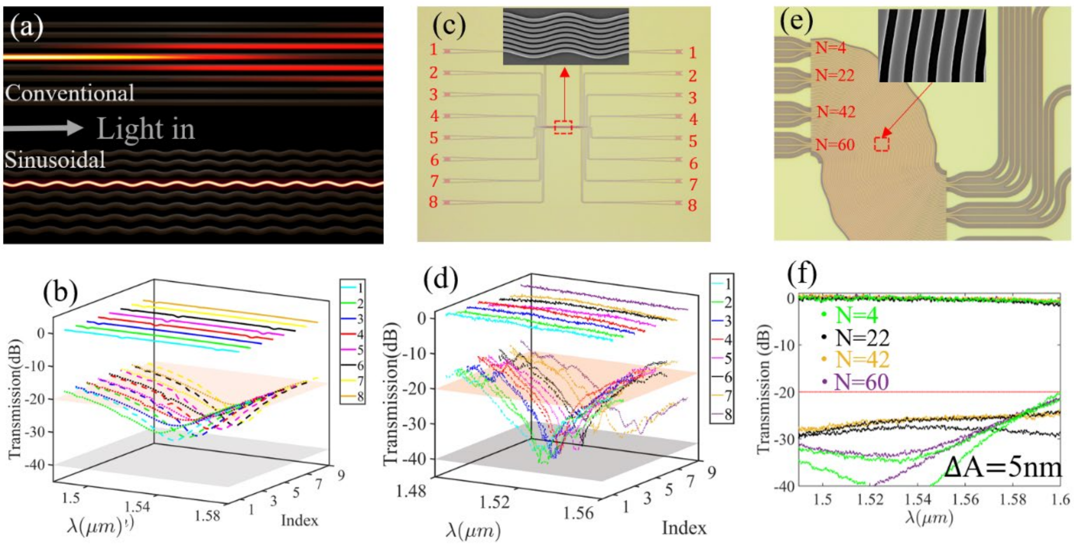

Fig. 4: (a) Comparison of the normalized field evolution between the proposed and conventional waveguide array with the same pitch of 750 nm at 1550 nm. (b) Simulated transmission and crosstalk of the proposed waveguide array of d=750 nm. Fabricated sinusoidal straight (c) and bent (e) waveguide array. The measured transmission spectra of the sinusoidal straight (d) and bent (f) waveguide arrays with waveguide separation of d=750 nm.

modulation with a uniformly varying amplitude. The bending radius for the innermost waveguide is 5 μm. As shown in Fig 4e, four ports (4^{th}, 22^{nd}, 42^{nd}, and 60^{th}) are chosen to measure the corresponding transmission and crosstalk.

Fig. 4f shows the measurement results when the amplitude difference of the shape-modulation between adjacent waveguides is $\Delta A = 5$ nm. Excellent crosstalk suppression -25 dB for the whole C-band and -20 dB for the wavelength range from 1480 nm to 1600 nm has been achieved.

Discussion

In conclusion, we propose and demonstrate a new approach, introducing AGF, to suppress the crosstalk in a half-wavelength pitched dense waveguide. The AGF could be realized through waveguide shape modulation. The experimental results show that for a straight waveguide array with AGF, minimum crosstalk of -35 dB and a -20 dB crosstalk bandwidth of about 40 nm. For a bent waveguide array with AGF, the crosstalk of less than -25 dB for the whole C-band and -20 dB over 100 nm bandwidth is proved. These results indicate that our sinusoidal dense waveguide array significantly suppresses the crosstalk and improves the integration density, which is essential in the optical phased array, optical delay lines, on-chip optical interconnects, and space-division multiplexing.

Device fabrication

The devices are fabricated on a standard SOI wafer with a 220 nm silicon membrane and 2 μm buried oxide. Grating couplers, sinusoidal waveguide array, and fan-in/out junctions were patterned simultaneously in one step with e-beam lithography using the Elionix ELS-F125G8 electron-beam lithography tool with ZEP-520A e-beam resist, followed by pattern transfer to silicon with inductively coupled plasma (ICP) etch using HBr and Cl_2.

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