Opto-Electronic Advances

News & Views
July 2025, Vol. 8, No. 7

DOI: 10.29026/oea.2025.250158 CSTR: 32247.14.oea.2025.250158

On-chip metasurfaces unlock efficient vector terahertz beams

Jitao Ji, Tao Li* and Shining Zhu*

An efficient on-chip platform for generating customizable vectorial optical fields is crucial and highly-pursued. While on-chip metasurfaces have opened up avenues for multi-functional coupling from on-chip surface wave to free-space propagating wave, they typically encounter the trade-off between extraction efficiency and wavefront accuracy. Recently, Prof. Lei Zhou's group pioneered a strategy employing geometric metal meta-atoms with low polarization conversion ratio to overcome this bottleneck and experimentally demonstrated generation of pre-designed terahertz vector beams with efficiency exceeding 90%. This approach establishes a generic, high-performance framework for advanced on-chip meta-devices.

Keywords: metasurface; optical field manipulation; surface wave; vectorial optical field

Ji JT, Li T, Zhu SN. On-chip metasurfaces unlock efficient vector terahertz beams. *Opto-Electron Adv* **8**, 250158 (2025).

With burgeoning applications in integrated photonics, waveguide-based display technology, microscopy imaging, LiDAR, etc., linking on-chip optical fields with free-space radiations is of great significance. This demands comprehensive control over near-field to far-field optical transformations in terms of multiple degrees of freedom including amplitude, phase, polarization and so on[1,2]. Unfortunately, conventional coupling schemes based on one-dimension grating couplers are often featured with large footprint, low efficiency and limited modulation capability, failing to meet the requirements of these advanced applications. Bridging the gap between surface waves and propagating waves thus remains an urgent priority.

In recent decades, the surge of metasurface technologies has revolutionized traditional frameworks for optical field manipulation and boosted versatile meta-devices with high integration[3,4]. Especially for on-chip metasurface, which combines metasurfaces with integrated optical waveguides, it makes a highly compelling choice to manipulate on-chip signals and realize novel photonic integrated devices with expanded functionalities and improved performances[5]. Under such circumstances, on-chip metasurfaces have been configured into an upgraded version of grating coupler and facilitates flexible conversion from surface wave to propagating wave with tailored wavefronts[6,7].

In pioneering work from several years ago, metal-dielectric-metal nanoantennas were utilized as resonant structure to constitute guided wave-driven metasurfaces[8], which offered potentials for high extraction efficiency but at the expense of wavefront fidelity due to strong interaction process between metallic resonant structure and surface wave. To address this problem, dielectric on-chip metasurface has been investigated to offer a feasible solution to precise phase control of guided wave

National Laboratory of Solid State Microstructures, Key Laboratory of Intelligent Optical Sensing and Manipulation, Jiangsu Key Laboratory of Artificial Functional Materials, Collaborative Innovation Center of Advanced Microstructures, College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, China.

*Correspondence: T Li, E-mail: taoli@nju.edu.cn; SN Zhu, E-mail: zhusn@nju.edu.cn

Received: 21 June 2025; Accepted: 24 June 2025; Published online: 10 July 2025

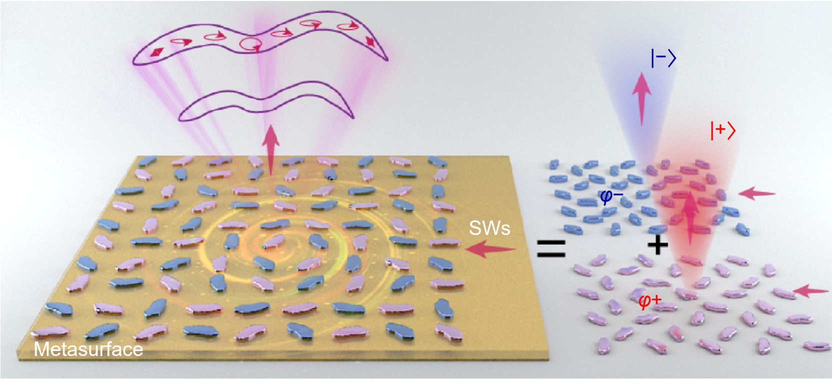

Fig. 1 | Schematic illustration of generating vector optical fields via two merged metasurfaces under surface wave excitation[12].

radiation whereas it suffers from relatively low working efficiency instead, typically no more than 10%[9–11]. Consequently, achieving high efficiency while maintaining precise wavefront shaping capability continues to be a challenge in existing on-chip metasurfaces.

In a recent paper published in *Opto-Electronic Science*, Prof. Lei Zhou and Prof. Shulin Sun, along with their colleagues, introduced a paradigm for ultra-compact on-chip devices that transform surface waves into pre-designed terahertz (THz) far-field beams with high efficiency[12]. On the basis of Pancharatnam-Berry (PB) mechanism, the proposed device employs a metal-insulator-metal (MIM) configuration composed of gold nanobars under surface wave excitation. As illustrated in the right side of Fig. 1, the elaborate design on the rotation angle of nanobars imparts additional phase gradient via PB phase. This selectively decouples the surface wave into free space for the desired circular polarization state (e.g. $|+\rangle$), while the unmodulated component with the orthogonal polarization state remain confined as surface waves due to wavevector mismatching. Such arrangement recycles incident surface wave back and therefore enhances the energy utilization of the device. More importantly, unlike conventional PB phase-based metasurfaces that maximize polarization conversion ratio (PCR), the authors intentionally adopted low-PCR meta-atoms in their design to enhance the tolerance of the structural perturbations. It should be mentioned, the reason why low-PCR metasurface still work rightly lies on the fact that the unmodulated surface wave would not be scattered out to bring background noises. In fact, similar design of on-chip integrated geometric metasurface free of background noises was also demonstrated and discussed in optical regime[11].

As proof of concept, the authors performed experimental demonstrations of unidirectional radiation in left circular polarization (LCP) channel and focused beams with right circular polarization (RCP), both achieving relative efficiency exceeding 90% at 0.4 THz. Furthermore, by leveraging spatial multiplexing strategy, they merged two metasurfaces responsible for generating LCP and RCP Bessel beams with opposite orbital angular momentum to establish a supercell structure. This architecture efficiently produced a radially polarized Bessel beam in the far field through interference, see Fig. 1. Experimental results exhibit excellent agreement with full-wave simulations, validating the device performance and design methodology.

This work showcases the ability to on-chip generate complex beams with arbitrary wavefronts and polarization in an efficient manner, which represents a significant leap towards the field of THz photonics and integrated optics. Future research could explore dynamic tunability for reconfigurable vector optical field generation or integration with active THz components for even more sophisticated functionalities. Overall, the implications of this work are far-reaching, promising to advance on-chip meta-device development and unlock new possibilities across optical communications, biomedical sensing and quantum optics.

References

1. Kim I, Martins RJ, Jang J et al. Nanophotonics for light detection and ranging technology. *Nat Nanotechnol* **16**, 508–524 (2021).
2. Ding YQ, Yang Q, Li YNQ et al. Waveguide-based augmented reality displays: perspectives and challenges. *eLight* **3**, 24 (2023).
3. Kuznetsov AI, Brongersma ML, Yao J et al. Roadmap for optical metasurfaces. *ACS Photonics* **11**, 816–865 (2024).
4. Li T, Chen C, Xiao XJ et al. Revolutionary meta-imaging: from superlens to metalens. *Photon Insights* **2**, R01 (2023).

5. Meng Y, Chen YZ, Lu LH et al. Optical meta-waveguides for integrated photonics and beyond. *Light Sci Appl* **10**, 235 (2021).
6. Huang HQ, Overvig AC, Xu Y et al. Leaky-wave metasurfaces for integrated photonics. *Nat Nanotechnol* **18**, 580–588 (2023).
7. Ji JT, Li J, Wang ZZ et al. On-chip multifunctional metasurfaces with full-parametric multiplexed jones matrix. *Nat Commun* **15**, 8271 (2024).
8. Guo XX, Ding YM, Chen X et al. Molding free-space light with guided wave–driven metasurfaces. *Sci Adv* **6**, eabb4142 (2020).
9. Fang B, Wang ZZ, Gao SL et al. Manipulating guided wave radiation with integrated geometric metasurface. *Nanophotonics* **11**, 1923–1930 (2022).
10. Shi YY, Wan CW, Dai CJ et al. Augmented reality enabled by on‐chip meta‐holography multiplexing. *Laser Photonics Rev* **16**, 2100638 (2022).
11. Ji JT, Wang ZZ, Sun JC et al. Metasurface-enabled on-chip manipulation of higher-order Poincaré sphere beams. *Nano Lett* **23**, 2750–2757 (2023).
12. Wang Z, Pan WK, He Y et al. Efficient generation of vectorial terahertz beams using surface-wave excited metasurfaces. *Opto-Electron Sci* **4**, 240024 (2025).

Acknowledgements

The authors acknowledge the support by the National Natural Science Foundation of China (Grant Nos. 62325504, 92250304, and 12174186) and Dengfeng Project B of Nanjing University.

Scan for Article PDF