

# Mid-Infrared Optoelectronic Waveguide Devices with 2D Materials

Liqiang Qi, Tianping Xu, Zhengkun Xing, Si Chen, Zunyue Zhang, Tiegeng Liu, and Zhenzhou Cheng\*

Mid-infrared (Mid-IR) integrated optics has tremendous applications in spectroscopic sensing, imaging, and ranging. Compared with visible light and near-IR wavelengths, the study of mid-IR photonic integrated devices is limited due to the need for more suitable materials and designs for constructing high-performance on-chip optoelectronic devices. Integrating emerging 2D materials with novel waveguide devices opens an avenue to boost the development of high-performance optoelectronic waveguide devices operating in the mid-IR wavelength range. This review summarizes the previous progress, current status, and future trends in exploring mid-IR optoelectronic waveguide devices with 2D materials. Specifically, the authors focus on the research efforts of developing passive photonic devices, modulators, photodetectors, and light sources. Then, the challenges and prospects in this area are discussed. The paper provides a valuable reference for researchers in infrared physics, optoelectronics, integrated optics, material science, sensing, and spectroscopy.

L. Qi, T. Xu, Z. Xing, S. Chen, Z. Zhang, T. Liu, Z. Cheng  
School of Precision Instruments and Opto-electronics Engineering  
Tianjin University  
Tianjin 300072, China  
E-mail: zhenzhoucheng@tju.edu.cn

L. Qi, T. Xu, Z. Xing, S. Chen, Z. Zhang, T. Liu, Z. Cheng  
Key Laboratory of Opto-electronic Information Technology  
Ministry of Education  
Tianjin 300072, China

Z. Cheng  
Georgia Tech-Shenzhen Institute  
Tianjin University  
Shenzhen 518055, China

Z. Cheng  
Department of Chemistry  
The University of Tokyo  
Tokyo 113-0033, Japan

Z. Cheng  
School of Physics and Electronic Engineering  
Xinjiang Normal University  
Urumqi 830054, China

The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/aprx.202400079>

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DOI: 10.1002/aprx.202400079

## 1. Introduction

The mid-infrared (mid-IR) spectral region, spanning from 2 to 25  $\mu\text{m}$ ,<sup>[1]</sup> has rich applications in free-space communication and ranging, as well as sensing and spectroscopy due to its coverage of three crucial atmospheric transparency windows (2–2.5, 3–5, and 8–12  $\mu\text{m}$ )<sup>[2]</sup> and the presence of fundamental vibrational transitions of biochemical molecules.<sup>[3,4]</sup> Compared with the short-wavelength range, performances of mid-IR optoelectronic integrated devices, namely, lasers,<sup>[5]</sup> modulators,<sup>[6]</sup> and detectors<sup>[7,8]</sup> were usually limited by the moderate properties of optical and optoelectronic materials. For instance, silicon or germanium-based photodetectors, widely used in CMOS sensors and optical communications,

cannot be utilized in mid-IR wavelengths due to unsuitable bandgaps of the materials. At the same time, silica has massive optical absorption to the mid-IR light, hindering the mid-IR applications of conventional optical devices in visible light and near-IR wavelengths. Consequently, exploring suitable materials and device designs for mid-IR optoelectronic integration has attracted significant research attention in recent decades.

2D materials, namely, graphene, black phosphorus (BP), and transition metal dichalcogenides (TMDs), possess unique optical and electronic properties, making them highly suitable for utilization in mid-IR wavelengths.<sup>[9]</sup> Typically, 2D materials exhibit strong light-matter interaction,<sup>[10]</sup> giant carrier mobilities,<sup>[11]</sup> and tunable bandgaps,<sup>[12]</sup> enabling efficient light absorption, modulation, and detection in the mid-IR wavelength region.<sup>[13,14]</sup> Moreover, integrating 2D materials with waveguide devices holds promise for developing ultra-compact and high-performance optoelectronic devices.<sup>[15–17]</sup> Silicon photonics, leveraging the well-established semiconductor device manufacturing infrastructures, provides an excellent platform for 2D-material integration without suffering from lattice mismatches.<sup>[18]</sup> Confining light within nanoscale waveguide devices with large evanescent fields enables strong light-2D-material interaction, enhancing their optical responses.<sup>[19]</sup> However, few papers have comprehensively reviewed the rapid development of emerging mid-IR optoelectronic waveguide devices with 2D materials.

This paper reviews the history, current status, and future trends of mid-IR optoelectronic integrated circuits with 2D

# Nonlinearoptic Waveguide Devices

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