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Feature issue introduction: mid-infrared optical materials and their device applications

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Abstract: The mid-infrared (mid-IR, 2 to 10 μm) is a technologically important spectral regime for sensing, imaging, and communications. In the past few years, there has been a surge of interest in novel mid-IR optical materials as well as their device implementations to address the increasing demands from these applications. The 22 papers in this feature issue represent a diverse cross-section of the latest technological advances in this field, spanning mid-IR light generation, propagation, manipulation, and detection functions in free-space, fiber, and planar platforms. In terms of material systems, semiconductors, glasses, plasmonic metals, as well as nanostructures specifically engineered for the mid-IR band, are all extensively covered. We hope that the readers will enjoy the kaleidoscopic view of the burgeoning field of mid-IR optics and photonics through this feature issue.

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1. Introduction

New optical materials play a pivotal role in enabling novel functional mid-IR optical devices and systems. In 2013, Optical Materials Express published a feature issue focusing on “Mid-IR Photonic Materials” which attracted significant interest and participation from the research community [1]. Since then, major strides in optical material development have continued to spur advances in mid-IR optics and photonics. Integrated on-chip mid-IR sources building on breakthroughs in semiconductor growth and integration [2–8], infrared fibers based on compositionally engineered glasses offering ultra-broadband transmission [9–11], high-performance infrared photodetectors and modulators made from 2-D crystals [12–19], and efficient mid-IR metasurface optics enabled by high-index dielectric materials [20–25] are among the most recent technological triumphs that underline the critical importance of mid-IR material innovations. Given the rapid growth of this field over the past five years, we consider it timely to launch a second feature issue dedicated to mid-infrared optical materials and their device applications.

The 22 papers in this feature issue can be roughly divided into six topical areas: 1) mid-IR laser materials and sources; 2) materials and strategies for infrared detection; 3) narrow-gap semiconductors and semiconductor nanostructures; 4) infrared glass materials and fibers; 5) integrated mid-IR photonics; and 6) plasmonic metals and nanostructures. In the following, we summarize the key results from the papers in the feature issue.
2. Mid-IR laser materials and sources

Since its invention in the 1990s, quantum cascade lasers (QCLs) have evolved into a mainstream mid-IR laser technology [26]. In this feature issue, Botez et al. demonstrated QCLs emitting at ~5 μm wavelength based on a step-taper active-region with resonant-tunneling extraction (STA-RE) concept [27]. The STA-RE design contributes enhanced internal efficiency of QCLs, and its advantage has been recently validated in QCLs emitting at 8-9 μm [28]. The authors reported effective suppression of carrier leakage, a record-high internal efficiency of 77% in their laser structures which is 30-50% higher than those of conventional QCLs emitting in the same wavelength range, and projected wall-plug efficiency values up to 41.2%.

In the 2-3 μm regime, low-phonon-energy crystals and glasses with rare earth doping are promising lasing media. Švejkar et al. reported a tunable mid-IR laser using erbium-doped SrF₂ crystals as a gain medium [29]. Taking advantage of the reduced non-radiative recombination in low-phonon-energy fluorides compared to oxides, the Er: SrF₂ laser operates at room temperature with a maximum output power of 1.3 W and a slope efficiency of up to 9.2%. Broadband wavelength tuning across more than 100 nm (2690 nm – 2813 nm) was also achieved using a MgF₂ birefringent filter, a significant improvement over prior results obtained in the same material system [30].

Also in this issue, a paper by Ning et al. describes the preparation of Fe²⁺-doped ZnSe nanocrystals using femtosecond laser ablation in solution [31]. A saturable absorber (SA) was fabricated by coating the synthesized Fe²⁺:ZnSe nanocrystals on a multiple-layer dielectric film, and the authors further applied the SA to realize passive Q-switching of an Er³⁺-doped ZBLAN fiber laser emitting at ~2.78 μm.

3. Materials and strategies for infrared detection

Unlike their near-IR or visible counterparts which offer extremely high performance at room temperature, mid-infrared detectors often require materials with less mature growth and processing protocols. Furthermore, they are far more susceptible to thermal noise and excessive dark current [32–34]. It is therefore important to understand the origin of dark current in mid-IR detectors. Marozas et al.’s paper discusses the mechanisms accounting for surface dark current in III-V semiconductor mid-IR detectors, which becomes increasingly significant as the detector size continues to scale [35]. Four sources of surface dark current are identified: majority carrier drift current, tunneling current, generation-recombination (G-R) current, and diffusion current. The relative importance of the dark current mechanisms in different device architectures is also discussed.

The paper by Liu et al. reported multi-wafer growth of large-format GaSb-based mid-IR photodetector structures via molecular beam epitaxy (MBE) [36]. Photodetectors made out of the GaSb-based 6.1 Å lattice constant family of materials are able to cover a wide spectral range (3 - 30 μm) leveraging the type-II band alignment in InAs/Ga(In)Sb-based strained-layer superlattices (SLS) [37]. However, the GaSb technology must scale to large substrate areas if it is to compete with HgCdTe, the incumbent technology for mid- and long-wave IR detectors. In this work, the authors demonstrated growth of GaSb-based nBn detector structures [38] on five 5-inch wafers or four 6-inch wafers, thus representing an important step towards practical implementation of large-format mid-IR detectors using GaSb-based materials.

The work by Yue et al. similarly studied GaSb-based semiconductors – in this case GaSbBi/GaSb quantum wells [39]. Alloys with Bi content up to 10.1% were grown by MBE and a band gap shrinkage of 32 meV/Bi% was measured. The result, also substantiated by a \( \mathbf{k} \cdot \mathbf{p} \) theoretical model, qualifies GaSbBi quantum wells as a promising material for mid-IR detectors and other optoelectronic devices.

Another new detector design discussed in this feature issue is still based on the HgCdTe material family yet assuming a different device architecture. Aleshkin et al. theoretically
investigated the characteristics of interband HgTe-CdHgTe quantum-well infrared photodetectors (QWIPs) [40]. The authors concluded from their study that the detector design can offer higher responsivity while having a comparable specific detectivity compared to traditional p-i-n photodiodes.

Upconversion as an alternative to direct photon detection can circumvent the need for narrow-gap semiconductors. Prior work on upconversion detection utilizes nonlinear oxide crystals which become opaque at wavelengths longer than 5 μm [41]. In their paper, Tseng et al. demonstrated that nonlinear AgGaS₂ crystals can be used to extend the wavelength coverage of the upconversion detection scheme to 9.4 to 12 μm wavelength range [42]. Pulses emitted from a QCL mixed with a 1064 nm laser beam in the crystal lead to the generation of an upconverted signal in the near-IR that can be readily monitored using a standard Si detector at room temperature and with superior time-domain resolution.

4. Narrow-gap semiconductors and semiconductor nanostructures

Interband transitions in narrow-gap semiconductors and intraband transitions in various semiconductor nanostructures are common pathways to access to the low transition energies commensurate with mid-IR applications. This topical category encompasses two theoretical studies on narrow-gap semiconductors: Chen et al. investigated the impact of Bi on band gap bowing in InP₁ₓ,Biₓ ternary semiconductors using first-principle calculations [43]. Sawamura et al. evaluated the nearest-neighbor sp³d⁵s* tight-binding model parameters for nine binary compound semiconductors using the hybrid self-consistent GW (QSGW) method, and concluded that the tight-binding model provides a reliable theoretical framework to guide superlattice design [44].

Ren et al. reported the growth of InAsP nanowire arrays with InAs and InAsSb inserts via catalyst-free metal-organic chemical vapor deposition (MOCVD) on InP substrates [45]. The work provides a new route to overcome the large lattice mismatch and incorporate narrow-gap semiconductors on InP. The ability to control the geometric parameters (e.g. periodicity and pitch) of the nanowire array via selective-area epitaxy further allows additional degrees of freedom to tailor the optical properties of the system for mid-IR applications.

The last article in this category reviews colloidal quantum dots (CQDs) and their use as mid-IR detector materials. Different from prior work capitalizing on interband transitions in narrow-gap CQDs [46,47], Jagtap et al. explored intraband transitions in self-doped mercury chalcogenide CQDs for photoconductive mid-IR detection [48]. The potential of transitioning to mercury-free alternative materials was also discussed.

5. Infrared glass materials and fibers

Thanks to their broadband infrared transparency, chalcogenide glasses (ChGs) and heavy metal oxide (HMO) glasses have already been widely applied in a wide range of mid-IR optical applications [49–57]. In addition, ChGs are also known for their exceptional Kerr nonlinearity, qualifying them as an ideal material candidate for nonlinear optics and photonics in the infrared [58–61]. In this feature, there are four articles that exploit the unique properties of these non-silicate glasses for mid-IR emission, transmission and nonlinear interactions.

Morris et al. described waveguide fabrication in bulk Ge₂₂As₂₀Se₅₈ glass (GASIR-1) using ultrafast laser writing [62]. Single-mode transmission was demonstrated in the mid-IR and a supercontinuum spanning 2.5 – 6.5 μm was generated in the waveguides. According to the authors, the result represents the broadest and the deepest mid-IR supercontinuum from an ultrafast laser inscribed waveguide to date.

Wu et al. fabricated suspended-core fibers consisting of two chalcogenide glasses, Ge₂₀As₂₀Se₁₅Te₄₅ (core) and Ge₉₀Sb₂Se₇₅ (cladding) [63]. The telluride glass exhibits strong optical nonlinearity. In addition, the suspended core geometry provides greater flexibility in engineering chromatic dispersion compared with standard step-index fibers. Using this fiber
platform, the authors demonstrated broadband supercontinuum generation spanning almost three octaves from 1.7 – 11.3 μm.

The low phonon energy of ChGs and HMOs also make them ideally suited as a host for rare earth ion emission in the mid-IR [64,65]. Along this line, the work by Li et al. investigated mid-IR luminescent properties of Pr³⁺-doped Ge-Sb-Se-Ga-I glasses [66]. The authors found that proper heat treatment above the glass transition temperature can lead to precipitation of GeSe₂ and Sb₂Se₃ nanocrystals in the glass matrix, which substantially enhances the photoluminescent emission intensity at 3.5 – 5.5 μm. In another article by Jia et al., the same research group also reported enhanced photoluminescence at 2.7 μm wavelength in Er³⁺/Ag-codoped bismuthate germanate glass as a result of local field concentration by the plasmonic Ag nanoparticle precipitates [67].

6. Integrated mid-IR photonics

Extending the operational wavelengths of integrated photonic devices and systems from the traditional telecommunication bands to the mid-IR has been intensively investigated in the past few years [68–74]. The apparent size, weight and power (SWaP) advantages of these chip-scale systems underpin their potential applications in imaging, free-space communications, and spectroscopic sensing [75–80].

Three papers in this feature align with such initiatives. Radosavljevic et al. present the fabrication and characterization of on-chip Vernier resonator filters on the Ge-on-silicon-on-insulator platform [81]. The filters exhibit loaded quality-factor of approximately 20,000 and side-peak suppression in excess of 20 dB. Moreover, the Vernier filter can be thermooptically tuned across its entire free spectral range of 108 nm with a time constant of 125 μs. The device can be used for wavelength selection in an external cavity laser.

Ge-rich SiGe is another material platform that potentially enables broadband mid-IR transmission up to 15 μm wavelength, only bound by the long-wave cut-off of Ge [82–84]. The paper by Liu et al. follows the same concept and further demonstrates the waveguide platform’s capability for evanescent wave sensing in the mid-IR [85]. The ability of this platform to sense low concentrations of methane gas is also evaluated.

The invited paper by Mashanovich et al. presents a comprehensive review of latest progress in mid-IR integrated photonics based on Group IV materials encompassing suspended Si, Ge-on-Si, and suspended Ge [86]. In addition to passive components, an impressive array of active devices such as modulators and detectors are also introduced, which constitute essential building blocks towards a fully-integrated mid-IR photonic platform.

7. Plasmonic metals and nanostructures

The strong light-matter interactions enhanced by plasmonic light confinement can be applied to applications such as laser beam shaping, chemical sensing, thermal imaging and heat scavenging, all highly relevant to the mid-IR spectral domain [87–91]. The operational wavelengths of noble metals, the classical material choice for plasmonics, are mostly limited to the visible and near-IR. Therefore, alternative material systems must be sought for expanding the spectral coverage to the mid-IR [92].

The works by Smith et al. and Cleary et al. in this feature issue address such a need by exploring metal germanides and ultra-thin indium tin oxide (ITO) films as alternative plasmonic metals [93,94]. Specifically, Smith et al. prepared germanides of Ni and Cu and compared their properties with those of Pd and Pt germanides in the mid-IR. They concluded that all but copper germanides are suitable material candidates for plasmonic applications in the 3 – 5 μm range. Cleary et al. quantified the optical and electrical properties of ITO films on Si with thicknesses between 10 to 100 nm [94]. Their work reveals that the Drude component of ITO’s electric permittivity becomes increasingly small with decreasing film
thickness, which they attribute to the presence of a non-electrical “dead layer” formed at the ITO/Si interface due to interfacial defects.

Graphene is another plasmonic material of significant interest in the mid-IR domain. Its Fermi level and hence optical characteristics can be electrostatically tuned, providing a facile solution to active plasmonics [95]. Habib et al. harnessed this unique feature of graphene to realize tunable plasmon induced transparency (PIT) in gold strips [96]. A 263 nm spectral shift of the PIT window at near 8 μm wavelength was experimentally measured by swinging the gate voltage from −0.6 V to 2.4 V. The grated-graphene-based tuning concept can be similarly applied to other types of active plasmonic devices.

The article by Ghaderi et al. instead focuses on improving the manufacturability of mid-IR metamaterial absorbers [97]. The novelty of the work is two-fold: 1) the metamaterial design is shape-tolerant such that they are amenable to fabrication using standard i-line UV lithography, and 2) the metamaterial is made out of CMOS-compatible materials including aluminum and SiO₂. Experimental measurement shows that optical characteristics of the metamaterial are maintained up to an incident angle of 30°. The validated manufacturability and good angular tolerance are important features that make the metamaterial absorber suitable for mid-IR MEMS device integration.

8. Conclusion

The mid-IR spectral domain presents immensely rich optical physics and a vast space for future technology innovations. The broad range of topics covered in this feature issue attests to the central importance of optical materials in enabling new mid-IR device applications. It is certainly the hope of the guest editor team that this feature issue will continue to inspire new research initiatives and prompt novel applications of mid-IR optical materials.

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