Feature issue introduction: mid-IR photonic materials

Juejun Hu,[1,*] Jerry Meyer,[2] Kathleen Richardson,[3] and Lawrence Shah[3]

[1]*Department of Materials Science and Engineering, University of Delaware, Newark, DE 19716, USA*
[2]*Code 5613, Naval Research Laboratory, Washington DC 20375, USA*
[3]*College of Optics and Photonics, CREOL, University of Central Florida, Orlando, Florida 32816, USA*
**hujuejun@udel.edu*

Abstract: The mid-infrared (mid-IR, 2.5 to 10 μm wavelengths) is a strategically important spectral band for an array of applications such as thermal imaging, chem/bio sensing, spectroscopy, infrared countermeasures, and free space communications. Mid-IR photonics have emerged as an active area of investigation in recent years, largely spurred by the rapid progress of cascade laser sources, uncooled detectors, and specialty mid-IR optical fibers. The 27 papers of this feature issue focus on the leading enabling material technologies for mid-IR photonics, and encompass recent advances in both active (lasers and detectors) and passive (fibers and waveguides) components. Linear and nonlinear photon-matter interactions in the mid-IR are also covered.

OCIS codes: (060.2390) Fiber optics, infrared; (130.3060) Infrared; (130.3120) Integrated optics devices; (140.3380) Laser materials; (140.3070) Infrared and far-infrared lasers; (140.5965) Semiconductor lasers, quantum cascade; (160.3130) Integrated optics materials; (160.4760) Optical properties; (160.6000) Semiconductor materials; (160.2750) Glass and other amorphous materials; (160.4236) Nanomaterials; (230.7370) Waveguides; (040.5160) Photodetectors; (310.6188) Spectral properties; (350.3850) Materials processing.

References and links

1. Y. Yao, A. Hoffman, and C. Gmachl, "Mid-infrared quantum cascade lasers," Nat. Photonics **6**(7), 432–439 (2012).
2. A. Hugi, R. Maulini, and J. Faist, "External cavity quantum cascade laser," Semicond. Sci. Technol. **25**(8), 083001 (2010).
3. I. Vurgaftman, W. Bewley, C. Canedy, C. Kim, M. Kim, J. Lindle, C. Merritt, J. Abell, and J. Meyer, "Mid-IR type-II interband cascade lasers," IEEE J. Sel. Top. Quantum Electron. **17**(5), 1435–1444 (2011).
4. W. W. Bewley, C. L. Canedy, C. S. Kim, M. Kim, C. D. Merritt, J. Abell, I. Vurgaftman, and J. R. Meyer, "High-power room-temperature continuous-wave mid-infrared interband cascade lasers," Opt. Express **20**(19), 20894–20901 (2012) (Gey.).
5. S. Maimon and G. W. Wicks, "nBn detector, an infrared detector with reduced dark current and higher operating temperature," Appl. Phys. Lett. **89**(15), 151109 (2006).
6. S. Keuleyan, E. Lhuillier, V. Brajuskovic, and P. Guyot-Sionnest, "Mid-infrared HgTe colloidal quantum dot photodetectors," Nat. Photonics **5**(8), 489–493 (2011).
7. S. Mirov, V. Fedorov, D. Martyshkin, I. Moskalev, M. Mirov, and V. Gapontsev, "Progress in mid-IR Cr^{2+} and Fe^{2+} doped II-VI materials and lasers," Opt. Mater. Express **1**(5), 898–910 (2011).
8. P. Kadwani, N. Modsching, R. A. Sims, L. Leick, J. Broeng, L. Shah, and M. Richardson, "Q-switched thulium-doped photonic crystal fiber laser," Opt. Lett. **37**(10), 1664–1666 (2012).
9. N. Carlie, J. D. Musgraves, B. Zdyrko, I. Luzinov, J. Hu, V. Singh, A. Agarwal, L. C. Kimerling, A. Canciamilla, F. Morichetti, A. Melloni, and K. Richardson, "Integrated chalcogenide waveguide resonators for mid-IR sensing: leveraging material properties to meet fabrication challenges," Opt. Express **18**(25), 26728–26743 (2010).
10. R. Soref, "Towards silicon-based Longwave Integrated Optoelectronics (LIO)," Proc. SPIE **6898**, 689809–1–689809-13 (2008).
11. A. Spott, Y. Liu, T. Baehr-Jones, R. Ilic, and M. Hochberg, "Silicon waveguides and ring resonators at 5.5 μm," Appl. Phys. Lett. **97**(21), 213501 (2010).
12. N. Yu, E. Cubukcu, L. Diehl, D. Bour, S. Corzine, J. Zhu, G. Höfler, K. B. Crozier, and F. Capasso, "Bowtie plasmonic quantum cascade laser antenna," Opt. Express **15**(20), 13272–13281 (2007).

#196819 - $15.00 USD Received 30 Aug 2013; published 30 Aug 2013

13. A. Ródenas, G. Martin, B. Arezki, N. Psaila, G. Jose, A. Jha, L. Labadie, P. Kern, A. Kar, and R. Thomson, "Three-dimensional mid-infrared photonic circuits in chalcogenide glass," Opt. Lett. **37**(3), 392–394 (2012).
14. A. Schliesser, N. Picqué, and T. Hänsch, "Mid-infrared frequency combs," Nat. Photonics **6**(7), 440–449 (2012).
15. B. Kuyken, X. Liu, R. M. Osgood, Jr., R. Baets, G. Roelkens, and W. M. Green, "Mid-infrared to telecom-band supercontinuum generation in highly nonlinear silicon-on-insulator wire waveguides," Opt. Express **19**(21), 20172–20181 (2011).
16. A. Marandi, C. W. Rudy, V. G. Plotnichenko, E. M. Dianov, K. L. Vodopyanov, and R. L. Byer, "Mid-infrared supercontinuum generation in tapered chalcogenide fiber for producing octave-spanning frequency comb around 3 µm," Opt. Express **20**(22), 24218–24225 (2012).
17. P. Berry, J. Macdonald, S. Beecher, S. McDaniel, K. Schepler, and A. Kar, "Fabrication and power scaling of a 1.7 W Cr:ZnSe waveguide laser," Opt. Mater. Express **3**(9), 1250–1258 (2013).
18. J. McCloy and B. Potter, "Photoluminescence in Chemical Vapor Deposited ZnS: insight into electronic defects," Opt. Mater. Express **3**(9), 1273–1278 (2013).
19. G. Zhu, X. Zhu, K. Balakrishnan, R. Norwood, and N. Peyghambarian, "Fe^{2+}:ZnSe and graphene Q-switched singly Ho^{3+}-doped ZBLAN fiber lasers at 3 µm," Opt. Mater. Express **3**(9), 1365–1377 (2013).
20. N. Bandyopadhyay, M. Razeghi, Y. Bai, Q. Lu, and S. Slivken, "Recent advances in mid infrared (3-5µm Quantum Cascade Lasers," Opt. Mater. Express **3**(11), 1872–1884 (2013).
21. M. Troccoli, A. Lyakh, J. Fan, X. Wang, R. Maulini, A. Tsekoun, R. Go, and C. K. N. Patel, "Long-Wave IR Quantum Cascade Lasers for emission in the λ = 8-12µm spectral region," Opt. Mater. Express **3**(9), 1546–1560 (2013).
22. C. Zhou, I. Vurgaftman, C. L. Canedy, C. S. Kim, M. Kim, W. W. Bewley, C. D. Merritt, J. Abell, J. R. Meyer, A. Hoang, A. Haddadi, M. Razeghi, and M. Grayson, "Thermal conductivity tensors of the cladding and active layers of antimonide infrared lasers and detectors," Opt. Mater. Express **3**(10), 1632–1640 (2013).
23. S. Höfling, R. Weih, A. Bauer, and M. Kamp, "Interband cascade lasers with AlGaAsSb cladding layers," Opt. Mater. Express **3**(10), 1624–1631 (2013).
24. G. Almuneau, Y. Laaroussi, C. Chevallier, F. Genty, N. Fressengeas, L. Cerutti, T. Taliercio, O. Gauthier-Lafaye, P.-F. Calmon, B. Reig, and J. Jacquet, "Oxide confinement and high contrast grating mirrors for Mid-infrared VCSELs," Opt. Mater. Express **3**(10), 1576–1585 (2013).
25. H. Munasinghe, A. Winterstein-Beckmann, C. Schiele, D. Manzani, L. Wondraczek, S. Afshar V, T. M. Monro, and H. Ebendorff-Heidepriem, "Lead-germanate glasses and fibers: a practical alternative to tellurite for nonlinear fiber applications," Opt. Mater. Express **3**(9), 1488–1503 (2013).
26. J. Bei, T. Monro, A. Hemming, and H. Ebendorff-Heidepriem, "Reduction of scattering loss in fluoroindate glass fibers," Opt. Mater. Express **3**(9), 1285–1301 (2013).
27. P. Lucas, Z. Yang, M. Fah, T. Luo, S. Jiang, C. Boussard-Pledel, M. Anne, and B. Bureau, "Telluride glasses for far infrared photonic applications," Opt. Mater. Express **3**(8), 1049–1058 (2013).
28. C. Bledt, J. Melzer, and J. Harrington, "Investigation of metal sulfide optical thin film growth in low-loss IR hollow glass waveguides," Opt. Mater. Express **3**(9), 1397–1407 (2013).
29. S. Geyer, J. Scherer, F. Jaworski, and M. Bawendi, "Multispectral imaging via luminescent down-shifting with colloidal quantum dots," Opt. Mater. Express **3**(8), 1167–1175 (2013).
30. Y. Zhong, P. Dongmo, L. Gong, S. Law, B. Chase, D. Wasserman, and J. Zide, "Degenerately doped InGaBiAs:Si as a highly conductive and transparent contact material in the infrared range," Opt. Mater. Express **3**(8), 1197–1204 (2013).
31. M. Nedeljkovic, A. Z. Khokhar, Y. Hu, X. Chen, J. S. Penades, S. Stankovic, H. M. H. Chong, D. J. Thomson, F. Y. Gardes, G. T. Reed, and G. Z. Mashanovich, "Silicon photonic devices and platforms for the mid-infrared," Opt. Mater. Express **3**(9), 1205–1214 (2013).
32. G. Roelkens, U. Dave, A. Gassenq, N. Hattasan, C. Hu, B. Kuyken, F. Leo, A. Malik, M. Muneeb, E. Ryckeboer, S. Uvin, Z. Hens, R. Baets, Y. Shimura, F. Gencarelli, B. Vincent, R. Loo, J. Van Campenhout, L. Cerutti, J. Rodriguez, E. Tournié, X. Chen, M. Nedeljkovic, G. Mashanovich, L. Shen, N. Healy, A. Peacock, X. Liu, R. Osgood, and W. Green, "Silicon-based heterogeneous photonic integrated circuits for the mid-infrared," Opt. Mater. Express **3**(9), 1523–1536 (2013).
33. P. Lin, V. Singh, J. Wang, H. Lin, J. Hu, K. Richardson, J. Musgraves, I. Luzinov, J. Hensley, L. Kimerling, and A. Agarwal, "Si-CMOS compatible materials and devices for mid-IR microphotonics," Opt. Mater. Express **3**(9), 1474–1487 (2013).
34. H. Lin, L. Li, Y. Zou, S. Danto, J. D. Musgraves, K. Richardson, S. Kozacik, M. Murakowski, D. Prather, P. T. Lin, V. Singh, A. Agarwal, L. C. Kimerling, and J. Hu, "Demonstration of high-Q mid-infrared chalcogenide glass-on-silicon resonators," Opt. Lett. **38**(9), 1470–1472 (2013).
35. H. Lin, L. Li, F. Deng, C. Ni, S. Danto, J. D. Musgraves, K. Richardson, and J. Hu, "Demonstration of mid-infrared waveguide photonic crystal cavities," Opt. Lett. **38**(15), 2779–2782 (2013).
36. Y. Zha, M. Waldmann, and C. Arnold, "A review on solution processing of chalcogenide glasses for optical components," Opt. Mater. Express **3**(9), 1259–1272 (2013).
37. L. Zhang, W. Zhang, X. Wang, P. Zhang, S. Dai, and Q. Nie, "Investigation of Ge20Sb15Se65 photonic crystal slab waveguides with slow light at infrared wavelength," Opt. Mater. Express **3**(9), 1438–1443 (2013).
38. L. Bi, N. Duan, H. Lin, L. Li, J. Hu, H. Lu, X. Weng, J. Xie, and L. Deng, "ZrO2-TiO2 thin films: a new material system for mid-infrared integrated photonics," Opt. Mater. Express **3**(9), 1537–1545 (2013).

39. M. Bache, H. Guo, and B. Zou, "Generating mid-IR octave-spanning supercontinna and few-cycle pulses with solitons in phase-mismatched quadratic nonlinear crystals," Opt. Mater. Express **3**(10), 1647–1657 (2013).
40. Y. Yu, X. Gai, T. Wang, P. Ma, R. Wang, Z. Yang, D. Choi, S. Madden, and B. Luther-Davies, "Mid-infrared supercontinuum generation in chalcogenides," Opt. Mater. Express **3**(8), 1075–1086 (2013).
41. D. Churin, T. Nguyen, K. Kieu, R. Norwood, and N. Peyghambarian, "Mid-IR supercontinuum generation in an integrated liquid-core optical fiber filled with CS_2," Opt. Mater. Express **3**(9), 1358–1364 (2013).
42. J. Jang, A. Haynes, F. Saouma, C. Otieno, and M. Kanatzidis, "Broadband studies of the strong mid-infrared nonlinear optical responses of $KPSe_6$," Opt. Mater. Express **3**(9), 1302–1312 (2013).
43. A. Machnev, P. Novozhylov, A. Poimanov, and I. Mel'nikov, "Single-pass parametric generator made of DFB diodes, specialty fiber amplifier, and periodically-poled lithium niobate," Opt. Mater. Express **3**(10), 1608–1615 (2013).
44. D. G. MacLachlan, R. R. Thomson, C. R. Cunningham, and D. Lee, "Mid-infrared volume phase gratings manufactured using Ultrafast Laser Inscription," Opt. Mater. Express **3**(10), 1616–1624 (2013).

The mid-infrared spectral regime is technologically important due to its relevance to such applications as thermal imaging, spectroscopic sensing, free-space communications and infrared countermeasures. The field of mid-IR photonics, which spans the generation, manipulation, transmission and detection of mid-IR radiation, has seen significant progress in the past decade, largely spurred by the rapid development of novel materials and device architectures operating at these wavelengths. Examples include the design and fabrication of quantum and interband cascade laser sources [1–4], the growth of unconventional narrow bandgap semiconductors and nanostructures [5,6], the synthesis of new IR glasses and optical ceramics in bulk, planar and fiber form [7–9], the development of novel processing methods for mid-IR photonic materials and device platforms [10–13], as well as the exploration of nonlinear optical interactions in mid-IR transparent materials [14–16]. The papers collected here summarize the forefront of exciting new research in these fields.

The papers in this feature issue can be divided roughly into five main topical categories: 1) laser materials and devices; 2) mid-IR fiber glasses; 3) semiconductors and nanostructures for mid-IR detectors; 4) material platforms for planar integrated components; and 5) nonlinear photon-matter interactions in the mid-IR.

Quantum cascade lasers (QCLs), interband cascade lasers (ICLs), and transition-metal-doped II-VI lasers are three cutting-edge technologies that provide complementary advantages in various overlapping ranges of the mid-IR. In this feature issue, Berry *et al.* report the demonstration of a Cr-doped ZnSe waveguide laser that produces 1.7 W at 2500 nm wavelength, which represents a six-fold increase compared to previous results for this promising laser class [17]. The authors attribute the higher output power to a reduction of thermal lensing effects in the channel waveguide gain structure, with the maximum output being limited ultimately by thermal quenching of the upper-state lifetime. McCloy *et al.* study photoluminescence (PL) properties of ZnS prepared by chemical vapor deposition and hot isostatic pressing [18]. Their investigation shows that these materials have highly complicated electronic defect structures, which depend critically on both the sample preparation method and orientation. Zhu *et al.* [19] demonstrate passive Q-switching of 3 μm Ho^{3+}-doped ZBLAN fiber lasers using a Fe^{2+}:ZnSe crystal and a graphene deposited fiber mirror as a saturable absorber. Bandyopadhyay *et al.* [20] and Troccoli *et al.* [21] review some of the latest advances by QCLs emitting in the 3 - 5 μm and 8 - 12 μm spectral ranges, respectively. Recent achievements highlighted by the Northwestern group include extension of the emission wavelength to as short as 3 μm, a record high QCL wallplug efficiency of 53% at 40 K, a peak output power of 190 W, and a room temperature continuous wave (CW) output power of 5.1 W, with 21% wall plug efficiency. Troccoli *et al.* compare the performance of longer-wavelength (8-12 μm) QCLs grown by molecular beam epitaxy (MBE) *vs.* metalorganic chemical vapor deposition (MOCVD). CW output powers exceeding 1 W and double-digit wallplug efficiencies are now attainable at room temperature. It has been noted that the performance of mid-IR interband cascade lasers degrades rapidly with increasing temperature. To identify the critical thermal bottleneck in these lasers, Zhou *et al.* [22] measure the in-plane and cross-plane thermal conductivities of the cladding layers and active quantum wells of type-II lasers andsuperlattice infrared detectors using the 2-wire 3ω method. The measurement results yield an exceptionally-low isotropic thermal conductivity of 0.49 W/m·K for the AlAsSb digital alloy. Höfling *et al.* [23] fabricate ICLs with quaternary bulk AlGaAsSb cladding layers, where the bulk claddings provide efficient mode confinement due to their low refractive index, comparable heat conductivity and a reduced current spreading. In an effort to explore an alternative mid-IR laser technology, Almuneau *et al.* [24] have fabricated and tested a VCSEL structure with lateral oxide confinement and a resonant grating reflector as the top mirror. The electroluminescence sharply peaks at 2.235 μm wavelength, although no lasing action is observed.

Since silica, the dominant optical fiber material for telecommunication bands, becomes opaque beyond 3.5 μm wavelength, alternative fiber-optic materials such as heavy metal oxides and chalcogenides are being explored for mid-IR transmission. Munasinghe *et al.* [25] report the fabrication and characterization of lead-germanate glass fibers and obtain a high Kerr nonlinearity index $n_2 = 56 \times 10^{-20}$ m^2/W in an optimized glass composition. Bei *et al.* [26] discuss methods to reduce optical loss and improve the mechanical strength of fluoroindate glass fibers. Lucas *et al.* [27] describe telluride chalcogenide glass composition engineering approaches to achieving glass stability, as well as long wave infrared transparency for IR fiber applications. These authors also demonstrate a telluride-based electrophoretic sensor in which the electrically-conductive telluride glass serves as both a capture electrode and an attenuated total reflectance (ATR) optical element for spectroscopic detection of biological species. As an alternative to traditional solid-core optical fibers, hollow glass waveguides (HGWs) capitalizing on metal-dielectric reflective coatings offer potential advantages such as high damage threshold and minimal end facet reflection. Harrington *et al.* [28] experimentally establish the film growth rates CdS and PbS dielectric thin films that enhance the mid-IR reflection in HGWs. These authors show that optimized deposition conditions allow films with large thicknesses to be achieved for the mid-IR region, as opposed to previous limitations which allowed for optimization in the near-IR only.

Two papers describe the development of advanced materials for mid-IR detectors. Geyer *et al.* [29] discuss an alternative approach to the multispectral imaging of photons spanning the UV to SWIR bands. UV photons, which normally fall outside the spectral response window of SWIR imagers, are absorbed by a quantum dot (QD) coating and then down-converted to IR photons that can be detected sensitively by the underlying SWIR imager with a high frame rate of 150 kHz. Zhong *et al.* [30] show in their paper that degenerately-doped InGaBiAs:Si grown by MBE can serve as a new transparent contact material for mid-IR photonics, in contrast to most conventional transparent conductive oxides (such as indium-tin-oxide, ITO) that become opaque due to free carrier absorption. Sheet resistances as low as 7 Ω/□ and high optical transmittances (> 70%) at wavelengths up to 10 μm were obtained simultaneously.

The new field of integrated planar mid-IR photonics is attracting growing research interest. Silicon, the mainstream substrate for microelectronics and silicon photonics, continues to provide an important material platform for mid-IR applications, given its high refractive index and transparency to wavelengths as long as 7 μm. In this issue, Mashanovich *et al.* [31] present a topical review of passive mid-IR silicon photonic devices, including waveguides, Mach-Zehnder interferometers, multi-mode interference (MMI) splitters, and an angled MMI multiplexer. The heterogeneous integration of other materials with silicon offers versatile photonic functionalities that are essential to an integrated photonic circuit. For example, Roelkens *et al.* [32] report the integration of GaSb photodetectors, laser sources, and PbS QD photoconductive detectors with silicon waveguides via an adhesive bonding process. Lin *et al.* [33] evaluate polycrystalline PbTe thin films deposited by thermal evaporation as a potential mid-IR detector material for monolithic integration with chalcogenide glass or pedestal silicon waveguides. Amorphous glasses, in particular chalcogenide glasses (ChG) and heavy metal oxides, represent another promising class of materials for integrated mid-IR

#196819 - $15.00 USD Received 30 Aug 2013; published 30 Aug 2013

photonics, given their broad transparency, high refractive indices, and amorphous structure that is compatible with monolithic integration on different substrates [34,35]. Along this line, Arnold *et al.* [36] provide an overview of solution processing as an alternative to vacuum-based deposition for ChG film formation. Their method is applied to the hybrid integration of ChG waveguides with QCLs. Zhang *et al.* [37] model slow light propagation in $Ge_{20}Sb_{15}Se_{65}$ chalcogenide glass photonic crystal slab waveguides. Bi *et al.* [38] systematically characterize the structural and optical properties of ZrO_2-TiO_2 thin films deposited by reactive sputtering. Mid-IR transparency of the material at $\lambda = 5.2$ μm is demonstrated by optical resonator measurements showing a loaded Q-factor of 11,000.

Six papers in this issue cover the rich physics and material science underlying nonlinear optical interactions in the mid-IR, as well as emerging device technologies that enable these phenomena to be exploited experimentally for practical applications. In particular, mid-IR supercontinuum generation via nonlinear interactions is a topic currently of intensive research interest. Bache *et al.* [39] describe a method for generating octave-spanning supercontinua and few-cycle pulses, by capitalizing on strongly phase-mismatched cascaded second-harmonic generation (SHG) in mid-IR nonlinear frequency conversion crystals. Yu *et al.* [40] summarize recent demonstrations of mid-IR supercontinuum generation in ChG materials, and report the experimental demonstration of flat supercontinuum generation in bulk ChG from 2.5 to 7.5 μm. Churin *et al.* [41] report supercontinuum generation in a liquid-core optical fiber filled with carbon disulfide (CS_2). The paper by Roelkens *et al.* [32] discuss the nonlinear optical interactions in c-Si and a-Si waveguides in the mid-IR range, including supercontinuum generation and parametric Raman amplification. Jang *et al.* [42] quantify the mid-IR nonlinear optical properties of $KPSe_6$ crystals: $\chi^{(2)} = (142.8 \pm 10.5)$ pm/V and $\chi^{(3)} = (4.7 \pm 0.6) \times 10^5$ pm^2/V^2. The observed strong optical nonlinearities indicate that the material can potentially be utilized for both second- and third-order mid-IR nonlinear optical applications. Mel'nikov *et al.* [43] demonstrate a pulsed mid-IR source with 10-ns pulse width, few hundred-microjoule energy, and repetition rate adjustable from 10 through 500 kHz based on parametric generation in periodically poled lithium niobate. As an example of applying nonlinear interactions to optical structure fabrication, MacLachlan *et al.* [44] fabricate and characterize volume phase gratings in gallium lanthanum sulfide ChG using ultrafast laser inscription, and obtain 1st order diffraction efficiencies exceeding 61% at $\lambda = 1.3$ μm and up to 24% at 2.64 μm.

In sum, the editors believe that expanding the operation wavelengths of photonic devices from the traditional telecommunications windows to the mid-IR offers immense opportunities for scientific exploration and technological advancement, as well as unique material science and device physics challenges that extend far beyond a simple wavelength scaling. It is our hope that this feature issue offers a timely overview of the dynamic and highly multidisciplinary field of mid-IR photonics, and will spur further research, development, and educational efforts in this area. We especially want to express of our genuine gratitude to all the authors and reviewers for their contributions. We also thank Dr. David Hagan for his support of this feature issue, and the OSA staff for their excellent work throughout the review and production processes.