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Mid-infrared, long-wave infrared, and terahertz photonics: introduction

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Abstract: This feature issue presents recent progress in long-wavelength photonics, focusing on wavelengths that span the mid-infrared (3–50 µm), the long-wavelength infrared (30–60 µm), and the terahertz (60–300 µm) portions of the electromagnetic spectrum. The papers in this feature issue report recent progress in the generation, manipulation, detection, and use of light across this long-wave region of the "photonics spectrum," including novel sources and cutting edge advances in detectors, long-wavelength non-linear processes, optical metamaterials and metasurfaces, and molecular spectroscopy. The range of topics covered in this feature issue provide an excellent insight into the expanding interest in long-wavelength photonics, which could open new possibilities for basic research and applications in industries that span health, environmental, and security.

1. Background

Unlike the ultraviolet and visible regions of the electromagnetic spectrum, which have been studied intensely over the last few centuries, starting with early experiments on the science and engineering of visible light by Newton, the infrared region of the electromagnetic spectrum is in a relative stage of infancy. While the visible spectral region is now defined by the International Organization for Standardization (ISO) as wavelengths in the 380–780 nm spectral range, the infrared spectral region consists of wavelengths beyond the long wavelength edge of the visible spectrum, namely all wavelengths in the 780 nm – 1 mm (1000 µm) range, and is rigorously subdivided into the IR-A (780 nm -1.4 µm), IR-B (1.4 µm - 3 µm), and IR-C (3 µm - 1000 µm) bands, the latter being further subdivided into the mid-infrared (MIR), 3 µm – 50 µm, and the far-infrared (FIR), 50 µm - 1000 µm, bands [ISO 20473, 2007].

Despite these formal designations for different spectral regions by ISO, the general research literature on infrared optics and photonics often uses different designations and different range definitions for various regions of the IR spectrum, including the MIR. For instance, the Dictionary of Earth Sciences (www.encyclopedia.com) defines the MIR range as covering the wavelength range between 8 µm and 14 µm, while other researchers designate this same range as long-wavelength infrared (LWIR). Astronomical researchers at IPAC and NASA (icc.dur.ac.uk) often designate the MIR spectral range as ~5 µm to ~ 30 µm, and the FIR as ~ 30 µm to ~ 300 µm.

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Independent of these designations, the research literature on photonics devices frequently uses several other several loosely-defined spectral regions, often with arbitrary boundaries, namely the near-infrared (0.8 μm – 3 μm), MIR (3 μm – 30 μm), FIR (30 μm – 60 μm), and terahertz spectral regions (60 μm – 1 mm), the latter corresponding to frequencies of 0.3 THz to 5 THz. As such, we have treated the exact nomenclature and frequency band designations in this Feature Issue as somewhat arbitrary, and have deferred to the band designations used by the authors; thus, the general focus of this Feature Issue is on "long wavelength photonics at wavelengths longer than 2 μm", with the spirit of long-wavelength photonics implying use of wavelengths in the "mid-infrared and beyond" all the way upto Terahertz frequencies (corresponding to wavelengths of several 100 μm or frequencies as low as 0.3 THz) corresponding to the "borderline" of what usually constitutes microwaves, i.e., up to ultralong wavelengths and ultralow frequencies that use technologies and techniques that are usually very different than those used in conventional photonics.

2. Motivation for this feature issue

The field of MIR and LWIR photonics continues to impact many application areas, and to advance technological access to these areas at longer and longer wavelengths through the development of new materials, devices, and techniques, such as the rapid emergence of frequency combs for applications in ultraprecise molecular spectroscopy and ultrasensitive molecular detection. As an example, the strong interaction of light with molecular vibrational and rotational resonances with MIR energies can be leveraged via both spatially selective and ultrasensitive imaging and molecular detection applications. Likewise, FIR and terahertz photonics aim to develop even longer wavelength portions of the spectrum through advancing the state-of-the-art in quantum and bulk materials, devices, and their applications. There has also been significant progress in the development of coherent FIR and terahertz sources, and in scientific fields such as nonlinear THz spectroscopy, which in turn have opened up exciting possibilities in materials characterization and development. However, FIR and terahertz devices, materials, and applications have developed slowly relative to the MIR and LWIR. While significant growth and maturity has been realized over the past several decades, long-wavelength photonic technologies are anticipated to experience numerous new innovations in materials and devices in the very near future. Nevertheless, despite the slower progress, strong applications have emerged in the FIR and terahertz portion of the spectrum in astrophysics, astrochemistry, biosensing, and homeland defense. While medicine is a large application space, LWIR technologies have had broad impact in many scientific and technological fields ranging from vortex beams (MIR to THz), quantum size effects, comb frequency generation, astronomy, nonlinear spectroscopy and molecular sensing to noninvasive sub-surface imaging probes (LWIR, THz) and defense-related countermeasure (IRCM) applications (MIR, LWIR).

This feature issue, aptly named "To the MIR and Beyond" in its original conception, is focused on the IR-C spectral region or "long wavelength photonics", namely the fields of MIR, FIR/LWIR, and terahertz photonics, which have all grown tremendously in the past two decades and have led to significant contributions to cutting-edge science, technology, and industrial applications. Although these spectral regions are often regarded as distinct portions of the spectrum, and have been covered individually by previous feature issues on related topics, many of the technological infrastructure and scientific methodologies of these three spectral regions (MIR, LWIR, and THz) are arguably more similar than they are different. In particular, the physics that underpins the generation (e.g. the use of quantum cascade lasers and nonlinear optics techniques), manipulation, and detection of electro-magnetic radiation in these three spectral regions is often very similar, and the areas of application often show significant overlap. The focus of this feature issue is on the entirety of these "optical community relevant" longer wavelengths ("the MIR and beyond"), and highlights the similarities between these apparently disparate spectral regions for the broad optics community as well as to "more narrowly focused" specialists in each of these areas, potentially spurring new opportunities for unique insights, new collaborations, new basic research and enhanced photonic systems. *In summary, this issue attempts to emphasize the similarities in these apparently disparate spectral regions that are also unified in a single label, namely the IR-C band, in the ISO designations*.

3. Contents of this issue

This feature issue, nicknamed "MLT", comprises a collection of 2 invited and 33 contributed papers on recent achievements on a broad range of topics on long-wavelength photonics, including advances in metamaterials, MIR glass ceramics, nanophotonics, long-wavelength plasmonics, nonlinear optics, optical fibers, sources, detectors, optical sensors, and integration.

3.1. Invited papers in this MLT feature issue

The 2 invited papers cover advanced materials and devices from the MIR to the THz, notably broad and comprehensive reviews on:

1. "Mid-infrared Light Sources Based on Ion-Doped Transparent Glass Ceramics" by Ren *et al*.,
2. "Terahertz Optical Fibers" by Islam *et al*.

The titles of these articles are self-explanatory and the reader is referred to these unique review articles for specifics.

3.2. Contributed papers in this MLT feature issue

The 65+ contributed manuscripts submitted for this MLT Feature Issue covered an extremely broad range of subjects on MIR, LWIR and THz optics and photonics. Nevertheless, the 33 papers accepted for publication (via the usual Optics Express refereeing and reviewing process) can be "loosely lumped" into 5 categories. The following highlights a few of the key papers in each category.

3.2.1. Sources of long wave radiation

The contributed papers exhibit several significant advances in the generation of long-wavelength light. These advances expand the envelope for long-wavelength optical sources by increasing the spectral limits of sources [1] and investigating and improving source performance [2,3,4]. T. Du *et al*. [1] present their work on a germania-fiber short-pulsed Raman laser emitting at 2.166 µm with tunable pulse widths of 0.9 to 4.4 ns and pulse energies up to 12.15 nJ. The team achieved emission in the short-wavelength end of the spectrum an all-fiber Raman laser by pumping a 22 m germania-core fiber using noise-like pulses from a 1981 nm fiber laser and a cavity mismatching technique. For the demonstrated laser, the maximum average output power exceeds 50 mW. The work opens new opportunities for Raman lasers and could provide a path towards low-cost fiber lasers. T. Dai *et al.* also demonstrate a sub-2.1 µm source [3]; however, their approach employs a unidirectional ring laser incorporating a holmium-doped gadolinium tantalite (Ho:GTO) crystal. The team demonstrates single-longitudinal-mode emission by leveraging the Faraday effect and measures an output power of 392 mW at 2068.33 nm. The measured M^2 factor is 1.1 and the slope efficiency relative to the absorbed pump power is 60.2%. The paper also reports single-longitudinal-mode output with powers up to 1.02 W using a second Ho:GTO crystal with the same parameters as the crystal in the ring laser as a power amplifier. D. A. Diaz-Thomas *et al.* investigate the performance of interband cascade lasers (ICLs) emitting at 3.3 µm that employ bulk claddings of AlGaAsSb rather than superlattice claddings of InAs/AlSb, which are typically used in ICLs [2]. Their approach leverages AlGaAsSb as a low-index cladding material

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to improve confinement, reduce the burden on ICL growth, and improve thermal conductivity of the cladding. The characterized devices exhibit internal quantum efficiencies up to 65% per active stage and emit at 3.33 μm in continuous wave mode up to 80 °C with 1 mW of power emitted from each facet. The emitted power increases to 12 mW per facet as the temperature is lowered to 20 °C. This performance is realized despite an internal loss of 15 cm^{-1} that could be due to absorption in sidewall oxidation or the AlGaAsSb layer; future work could lead to even higher performance ICLs that incorporate bulk cladding.

3.2.2. Physics of FIR materials, structures and frequency combs

In addition to coherent emission, the feature issue also presents advances in the understanding of radiative relaxation in silicon-based heterostructures [5], structures for selective absorption and thermal emission [6], and techniques for understanding the physics of MIR and terahertz frequency combs [7]. Ciano *et al.* study the radiative relaxation of n-type Ge/SiGe quantum wells that are optically excited using a free-electron laser [5]. The samples, grown via ultra-high vacuum chemical vapor deposition are optically excited at 10 THz, resulting in a non-equilibrium population of the third level in a coupled quantum well structure. Photoluminescence is observed at 4 THz, which can be related to an optical transition from the third to second levels in a coupled quantum well, with the possible of the second-to-first level transition also contributing to the emission. This work offers promising advances towards ultimately realizing electrically-injected, silicon-based quantum cascade lasers operating at THz frequencies. Z. Zhao *et al.* propose and study numerically an all-dielectric multilayer material that that absorbs weakly in the 8-14 μm atmospheric window and strongly (up to 95%) in a 1.2 μm wide spectral region outside the atmospheric window [6]. Additionally, the proposed structure depends weakly on polarization. Such a material is useful for suppressing thermal emission of long-wavelength light and could have uses in thermal-protective coatings. Finally, Han *et al.* discuss the limits of Shifted Wave Interference Fourier Transform Spectroscopy (SWIFTS) a technique that has found use for characterizing the temporal profile and coherence of long-wavelength frequency combs, including quantum cascade laser and interband laser frequency combs [7]. The authors discuss the how phase noise and non-idealities in the comb frequency spacing influence the sensitivity of SWIFTS and discuss how the technique is applicable to chirped pulses and FM combs. The paper concludes by applying this new analytic scaffolding to experiments using the chirped output of a femtosecond laser.

3.2.3. FIR detectors and microresonators

Beyond sources, progress in optical devices and detectors is reported, including device models for graphene/black-AsP FIR photodetectors [8] and high-Q diamond microresonators, which is also selected as an Editor's Pick [9]. V. Ryzhii *et al.* develop and present device models for FIR interband photodetectors that incorporate graphene-layer sensitive elements and blocking layers of black phosphorus or black-arsenic. These devices operate at wavelengths from 6-12 μm and there is potential for extending their operation to the terahertz via strong applied electric fields. The paper details a device model and the follow-on discussion includes terminal current, dark-current gain and voltage characteristics, detector responsivity, the limitations of the model, and more. The authors demonstrate how under certain conditions these devices can significantly reduce dark-current gain and elevate photoconductive gain, and ultimately how these detectors might compete with other FIR detector technologies. Y.-J. Lee *et al.* fabricate high-Q microresonators that operate at wavelengths beyond 9 μm using single crystal diamond substrates and inductively coupled plasma reactive ion etching. The authors characterize the photonic devices at room-temperature using a tunable quantum cascade laser coupled via free-space to the resonators. The characterized microdisc resonators exhibit quality factors that exceed 3000; more than an order-of-magnitude improvement over prior work on high-Q resonators for wavelengths

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beyond 9 µm. The authors also demonstrate that the measured free spectral range agrees well with the predicted value obtained by calculating the effective modal index.

3.2.4. Long-wavelength metamaterials and nanophotonics

Advances in long-wavelength metamaterials and nanophotonics are also featured in this issue. A. Pander *et al.* investigate the role of geometry on the total reflectance for metamaterials comprising carbon nanotube forests in spectral window spanning from 2–10 µm [10]. The authors fabricate split ring resonator structures from high-density, vertically-aligned single-walled carbon nanotube forests using focused ion beam etching after nanotube growth. They study the influence of the gap width and depth and overall metamaterial height on the unpolarized reflectance spectra. The authors demonstrate a reduction in the total reflectance by 15% through controlling the resonator gap width and depth; additionally controlling the resonator height through the nanotube growth process results in a reduction in the total reflectance by 25%. I. Avrutsky *et al.* report the design and experimental verification of MIR filters that exhibit narrow-band transmission over a large range of incident angles [11]. The design of the filters leverages dense arrays of dielectric nano-resonators in a metal film. The authors examine numerically various nano-resonator arrays using a scattering matrix algorithm and then fabrication and characterize a one-dimensional filter featuring embedded Ge resonators in Ag on a BaF_2 substrate. For light with a transverse magnetic polarization, transmission is around 85% at 6.1 µm with a full width at half maximum of $\Delta\lambda = 1.16$ µm. As the incident angle is increased from 0 to 60 deg., the peak transmission varies between 85 to 90%, and this shift in the wavelength of the peak transmission is much smaller than $\Delta\lambda$.

Progress in metasurfaces at terahertz frequencies is also reported, including novel coding schemes for designing beam splitters [12] and ultra-wideband absorbers realized via self-assembly methods [13]. X. Xing *et al.* propose and experimentally verify a 1-bit coding scheme for designing metamaterial beam splitters using coding theory [12]. Their approach features an offset coding sequence that allows designs to incorporate metasurface elements that are non-integer multiples of the length of a single unit cell. The authors demonstrate how this offset coding sequence imparts extra degrees of freedom in the antenna design process. They verify their approach by fabricating a metasurface comprising silicon pillars on a silicon substrate. Comparing the measured angular intensity distribution shows good agreement with simulation. D. Yang *et al.* demonstrate a terahertz metamaterial absorber on a flexible substrate that is realized via micro-template-assisted self-assembly. The fabricated terahertz absorber metasurface is a sandwich design where arrays of ZrO_2 (Zirconia) microspheres are arranged via templating between polymide and copper films. For metasurfaces with this periodic arrangement, a maximum absorption of 92.5% at 0.745 THz that is polarization independent is observed. In a non-periodic arrangement where the microsphere are arranged more compactly, the peak absorption shifts to higher frequencies and the bandwidth of strong absorption increases: A spectral region centered at 1.8 THz with a bandwidth of 1.2 THz where the absorption is greater than 90% is observed.

3.2.5. MIR to THz spectroscopy

Finally, the feature issue includes several contributions that advance spectroscopy in the MIR and terahertz. M. Gianella *et al.* present high-resolution, gapless spectra over the entire comb range of quantum cascade laser frequency combs, covering a spectral window of 55 cm^{-1} centered around 1200 cm^{-1} with a resolution of 0.001 cm^{-1} (30 MHz). The authors demonstrate how gapless spectra, where the spectral point spacing is smaller than the spectral resolution, can be achieved by interleaving multiple spectra that are offset. Their approach reduces the spectral point spacing of the comb, determined by the free spectral range of the lasers, by more than four orders of magnitude. The authors demonstrate the effectiveness of their technique by measuring the low-pressure gas phase absorption and dispersion spectra of methane, where the absorption

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line has a width of approximately 400 MHz. S.-Y. Jeong *et al.* propose and demonstrate an analytic method to find resonant peaks of biomolecules in aqueous environments. Their approach involves fitting the absorption coefficient with Gaussian and Lorentzian functions after baseline correction. To demonstrate their approach for comparison to other method, the authors measure the terahertz absorption of 5-methylcytidine (5-mC) and methylated DNA using a conventional THz time domain transmission system with a femtosecond oscillator. Two absorption peaks are identified for both samples in the 0.2 to 2.5 THz spectral region. U. Griskeviciute *et al.* demonstrate Ge-on-Si waveguides that are low-loss and single-mode, making them useful for sensing in the molecular fingerprint regime [14]. They demonstrate waveguide spectroscopy using Ge-on-Si rib waveguides that are coated with thin films of polymethyl methacrylate (PMMA) and thermally-cured hydrogen silsesquioxane (HSQ) resist, which exhibit absorption in the MIR due to C-O-C and Si-O-Si stretching bonds, respectively. The authors investigate how the width of the waveguide influences the modal overlap with material and the top of the rib waveguides, influencing the amount of light that can be absorbed. They also demonstrate how the dynamic range of the measurement can be improved by using multiple waveguides with different lengths covered by the absorbing material.

4. Relevant MLT-related feature issues in other journals

Because of the importance of these spectral regions, there have been several feature issues in numerous journals on the individual spectral regions during the past decade, with a much more rapid growth in such feature issues in the past 4 years, but none—to the best of our knowledge—since 2018. Of the 5 most significant feature issues that we were able to find, two focused on biomedical technologies and applications for the mid-infrared (*Biomedical Optics Express*, 2016, 2018), one on MIR laser sources an applications (*JOSA B*, “MIR Coherent Sources and Applications,” 2018), another on MIR materials (*Optical Materials Express,* “Mid-infrared Optical Materials and their Device Applications,” 2018), and the last (*APL Photonics*, “Frontiers on THz Photonic Devices,” 2018) emphasized electronic approaches to THz generation, control, and detection. We are including links to these 5 feature issues here for the benefit of readers of this “MLT” Feature Issue:

- *Biomedical Optics Express*: Mid-infrared Lasers for Medical Applications (2018)
- *APL Photonics*: Frontiers on THz Photonic Devices (2018)
- *Optical Materials Express*: Mid-infrared Optical Materials and their Device Applications (2018)
- *Journal of the Optical Society of America B*: Mid-Infrared Coherent Sources and Applications (2018)
- *Biomedical Optics Express*: Biomedical Applications of Terahertz Imaging Spectroscopy (2016)

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