

Chapter 6 – SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

Mid-infrared laser technology is critical to the development of active sources for defeating a growing spectrum of heat-seeking missiles, as well as for remote sensing of targets and threats. These coherent sources must be resistant to environmental changes, and sufficiently compact and conformable to fit in a variety of platforms including large transports, combat aircraft, helicopters, and even UAVs. Fiber lasers have distinct advantages over conventional bulk solid-state lasers for these applications. Their optical confinement reduces the need for free space optics which are sensitive to misalignment, and to such environmental conditions as dust, vibration, and moisture. The small dimensions of the modes propagating in the core of the fiber provide low-threshold and high-gain characteristics with near-maximum efficiency. Their inherent geometry simplifies thermal management and supports distributed system architectures.

Fiber lasers and fiber technology devoted to telecom applications are very well developed and sources delivering kW output powers have been demonstrated. Recent advances in the 2 μm wavelength range have also been demonstrated, but there is still a lack of fiber components. Passive transport fiber and fiber-based optical devices for the mid-IR are still rare, lossy and relatively fragile. Theoretical modelling and designs of fiber lasers emitting beyond 3 μm have been done, but demonstrations have been limited primarily to supercontinuum devices. Extending into the mid-IR the considerable advantages of fiber technology would provide laser sources that are efficient, robust, compact, potentially high in power, and spectrally suited to critical military applications like infrared countermeasures.

For this reason, the SET-170 Task Group focused its efforts on fiber sources operating at wavelengths longer than 3 μm , and fibers based on glasses other than silica. By sharing our diverse expertise, facilities, and materials, we were able to make progress in each of the three areas outlined in our programme of work.

In investigating direct lasing in fibers, we chose to focus on two rare earth dopants: dysprosium (Dy^{3+}) and holmium (Ho^{3+}), with lasing transitions at 4.3 μm and 3.9 μm respectively which have been demonstrated in other host materials. We selected fluoroindate fiber as the host material, because of its broader mid-IR transparency and lower phonon energies relative to the more-developed ZBLAN. Initial spectroscopic evaluation was done on glass samples doped with each rare-earth ion, due to the much greater cost of pulled fiber. This led to the abandonment of Dy^{3+} :fluoroindate as a candidate, due to the inability to observe any fluorescence on the desired transition.

Work with Ho :fluoroindate glass material proved much more successful. Spectroscopic analysis was conducted, specifically measurement of absorption, emission, and fluorescence lifetime, including measurements at low temperature using a cryostat system. The Ho^{3+} transition at 3.9 μm suffers from an unfavorable lifetime ratio, with the upper laser level lifetime typically two orders of magnitude shorter than that of the lower level, resulting in significant bottlenecking. Spectroscopic results were therefore critical as inputs to a model to evaluate the possibility of developing a viable Ho :fiber laser, and to identify a suitable fiber specification. Modelling results indicate that, despite the short lifetime, efficient lasing is possible in a double-clad fiber given the correct choice of concentration, taking advantage of up-conversion processes to help recirculate the active ions. Cascade lasing of the 2.9 μm transition improves performance significantly by alleviating the bottlenecking at the lower laser level, caused by its much longer lifetime relative to that of the upper laser level. Co-doping is also proposed as a means of relieving the bottlenecking, but appears not to help in this case.

The most significant achievement on the direct lasing task is demonstration of lasing in a sample of Ho :fluoroindate glass. A flashlamp-pumped Cr^{3+} :LiSAF laser operating at 890 nm pumped the Brewster-cut sample, in a cavity originally assembled using a crystal of the better-known Ho :BYF material. Results were modest: just over 5 mJ of output, and a slope efficiency of 1.3%. This is the first demonstration of lasing in

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this material, however, and given the nature of the sample and the far from optimal resonator conditions, bodes well for the performance of a Ho:fluoroindate fiber. A journal paper on these results is in preparation.

Work on frequency conversion in fibers focused on obtaining broadband mid-IR output via supercontinuum generation, specifically with pump pulses on the picosecond or nanosecond scale for greater average power than most sources reported to date. The end-goal is development of ruggedized, ready-to-use, multi-watt supercontinuum sources. Highlights of the results obtained by the SET-170 Task Group include:

- Demonstration of the highest average power (0.565 W) and the broadest spectrum (1.9 – 4.8 μm) directly emitted from a step-index chalcogenide (As_2S_3) fiber supercontinuum source;
- The first demonstration of watt-level (2.09 W in the 1 – 3.05 μm spectral band) and broadband (2.7 – 4.7 μm) mid-IR supercontinuum generation in a step-index fluoroindate fiber;
- The first demonstration of watt-level (1.08 W) supercontinuum generation (1.9 – 3.6 μm) in ZBLAN fiber pumped by an actively Q-switched and mode-locked Tm-doped fiber laser;
- The first demonstration of watt-level (1.25 W in the 1.8 – 4.15 μm spectral band) supercontinuum generation in a step-index ZBLAN fiber pumped by a fast gain-switched Tm-doped fiber laser and amplifier system; and
- Demonstration of the most efficient supercontinuum power distribution towards the mid-IR, with over half the output at wavelengths longer than 3 μm .

Practical realization of high average power mid-IR supercontinuum sources that meet military requirements remains a challenge, in terms of both the pump laser system and the non-linear fiber itself. The most significant factors limiting the long-wavelength edge of the supercontinuum spectrum are fiber non-linearities, bend-induced loss and bulk absorption. The most promising non-linear fibers are telluride, chalcogenide and fluoride-based fibers. Tellurides and chalcogenides have broad absorption and high non-linearity, but are susceptible to thermally induced damage at high powers. Fluoride fibers demonstrate better power handling, especially with careful thermal management, with the fluoroindate fiber featured in many of our results offering broader mid-IR transparency than the more familiar ZBLAN, covering the entire 3 – 5 μm region. An average output average power of > 20 W can be expected from a single-mode fluoride fiber covering the mid-IR band within the next 2 – 5 years.

The third task, fiber pump sources for bulk frequency conversion, considered pumping strategies for ZGP, PPLN, and OPGaAs, representing the current spectrum of non-linear materials from birefringent crystals to quasi-phase-matched materials based on poling of ferroelectric crystals, and orientation-patterned growth of semiconductors. While successful and even impressive device demonstrations have been reported with each of these materials, most still rely on bulk crystal lasers as pump sources. Progress is still needed on fiber-based pump sources as well as optical fiber components in this wavelength region, to support the eventual goal of all optically confined systems.

A particularly intriguing result of this task was OPGaAs OPO modelling which suggests that it may be possible, even practical, to pump OPGaAs at wavelengths as short as 1550 nm despite the material's well-known two-photon absorption in this region. A key limitation of OPGaAs has been the need to pump it at wavelengths longer than about 1.7 μm , which rules out the many mature and commercially available lasers operating around 1 μm and 1.5 μm , based on Nd, Yb, and Er active ions. Unfortunately OPGaAs material with the right pattern was not available during the Task Group's tenure, so we were unable to investigate this experimentally and it is left as future work. New materials that do not have 2-photon absorption in this region such as OPGaP are being developed, but the relative maturity of OPGaAs makes the prospect of being able to pump it at these shorter wavelengths tantalizing.

The programme of work laid out at the start of SET-170 was decidedly ambitious, and not all activities under every task could be completed successfully, due partly to the inevitable technical challenges that arise, as well as to the familiar financial, staffing, and schedule constraints. Decisions on how to proceed were made with an eye to maximizing the Task Group's contribution to the field given resources available. To that end, we were successful in that each task produced results that were noteworthy, and more importantly, useful in the further study of mid-IR fiber lasers. The Task Group activities resulted directly in 10 journal publications, plus two planned; as well as several conference presentations and proceedings – these are listed in Annex B.

Recommendations for future work are best grouped by task, following the programme of work.

Direct Lasing in Fibers

- Lasing of the Ho:fluoroindate glass sample was quite encouraging, but lasing still remains to be demonstrated in an actual fiber pulled from similar material, whose design is based on results obtained on this task. While any demonstration of lasing will be scientifically interesting, a practical device based on this gain material will require a more convenient pump source than Cr:LiSAF, specifically a diode laser. While diode lasers at the needed wavelength of ~ 890 nm are available, the unfavorable lifetime ratio on the desired transition limits energy storage in such a way that diode pumping at useful repetition rates and duty cycles may be quite a challenge.
- The Dy³⁺ ion was abandoned early on due to an inability to see any fluorescence at the 4.3- μ m transition of interest in the two samples available. These were doped with $\sim 1 - 2$ % Dy, and it may be enough simply to use more highly doped material. It is worth revisiting this material, and at least modelling gain on this transition using published results for similar materials as a starting point. The slightly longer wavelength may be even more useful than the 3.9 μ m Ho³⁺ transition.
- In terms of host materials, the present work focused on fluoride glass, specifically fluoroindate glass with its lower phonon energies and longer wavelength transmission relative to the more established ZBLAN. Chalcogenide fibers have long been attractive due to their transparency at even longer wavelengths, but the lack of stable sites for the dopant has frustrated attempts to pull usable fibers from the glass, leaving tantalizing spectroscopic results, but no lasers. Addressing the relevant glass chemistry issues to create stable sites for the ions would be a significant advance, and would open a whole new host fiber system for development. Of course there are yet other fibers worth considering, such as tellurites and other fluoride compositions.
- More broadly, there is the question of whether rare-earth-doped lasers of any kind are inherently limited vis-à-vis most military applications simply due to their narrow emission bands and minimal tunability. Countermeasure systems require wavelength agility to keep up with the variety of threat sensors in operation, and most remote sensing applications require much more broadband output. An obvious alternative is lasers based on transition metal ions like Cr²⁺ and Fe²⁺, but successful incorporation of these ions into fibers has proved elusive. Development of a viable transition-metal-doped fiber would be a significant advance in mid-IR fiber technology.

Frequency Conversion in Fibers

In addition to overall output power, a principal concern for mid-IR supercontinuum sources is the fraction of output power at longer wavelengths ($\lambda > 3$ μ m). This directly affects their practical use in such areas as direct infrared countermeasure or infrared spectral fingerprinting. This concerns both the non-linear fibers themselves, as well as the pump lasers. The most significant factors that limit the long-wavelength edge of the supercontinuum spectrum are fiber non-linearities, fiber material absorption, and bend-induced loss. Addressing these factors is a particularly pressing direction for future research.

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Tellurite and chalcogenide fibers are characterized by very high non-linearity facilitating efficient spectrum extension over short fiber lengths, but are susceptible to thermally induced damage at high powers, thus limiting the output average power < 2 W. Improved thermal management and heat dissipation techniques may help, but improvement in the material quality of the fibers themselves may be necessary to achieve useful power levels.

- Fluoride fibers have shown better power-handling ability while using only modest thermal management strategies, but so far are limited to around $5.5 \mu\text{m}$ in transparency.
- The entire category of microstructured fibers was not addressed in this work because the achieved output power has generally been low, i.e. less than 100 mW in the mid-IR spectral range. This may bear reconsidering as fiber fabrication methods and the resulting devices continue to develop.
- Work on this task was limited to supercontinuum generation based on the interests and expertise of Task Group participants. An obvious extension is to consider fiber Raman lasers, or fiber-based OPO and OPA. These technologies have received increasing interest in recent years. While they will not provide the broad spectral output of a supercontinuum device, they offer the possibility of a more narrowband but tunable source when paired with a tunable pump laser. Successful four-wave-mixing processes in particular, however, have relied on microstructured optical fiber which is even more costly than the custom fluorindate fiber necessary for demonstrating a Ho:fluorindate fiber laser.

Fiber Pump Sources for Bulk Frequency Conversion Devices

- The most pressing recommendation on this task is to verify experimentally whether OPGaAs can be pumped at $1.5 - 1.6 \mu\text{m}$, and if so, to establish the potential and limitations of this method as an alternative to the usual $2 \mu\text{m}$ pumping.
- The peak power or pulse energy available from a fiber laser continues to be an issue in pumping frequency conversion devices, since the non-linear process is intensity-driven. Damage to fiber facets or splices is neither uncommon nor trivial to repair, especially in a packaged device. Simply increasing the core size is generally not an option, as a good Gaussian beam profile is also required. Clever approaches like tapered end caps provide some relief, but this remains an area requiring further development.
- Finally, while an optimized fiber pump source is all well and good, reaching the end goal of an all-optically-confined system will also require the development of fiber-based components like isolators, modulators, switches, and beam combiners. These components are often not exciting or eye-catching enough to attract the funding necessary for their proper development, yet they can easily end up as the weak (or missing) link in an otherwise high-performing system, limiting the success of the system as a whole.

The SET-170 Task Group recommended, and the Fall 2013 SET Panel Business Meeting approved, creation of a new Exploratory Team to continue the collaborative investigation of mid-IR fiber-based sources. This ET, which we hope will lead also to a new Task Group, will consider these recommendations along with ongoing developments in the field of fiber lasers, to identify the best way forward and outline a new programme of work. As before, we expect that we will be able to accomplish more on behalf of NATO and our individual Nations through sharing our resources and expertise than any of us could accomplish alone.