Technical Evaluation Report

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INTRODUCTION

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. 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. Their inherent geometry simplifies thermal management and supports distributed system architectures. Although recent advances in fiber laser technology have been significant, with output powers in kW demonstrated by several research groups, no fiber laser has yet been demonstrated at wavelengths longer than 3 microns, the low end of the mid-IR atmospheric transmission window. Passive transport fiber and fiber-based optical devices for the mid-IR are still rare, lossy and relatively fragile. 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.

THEME OF WORKSHOP

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. Theoretical modelling and designs of fiber lasers emitting beyond 3 µm have been done but no fiber laser has yet been demonstrated. State-of-the-art, issues, challenges and potential of mid-IR fiber technologies were the ocus of the workshop discussion.

PURPOSE AND SCOPE OF WORKSHOP

The purpose of this workshop is to assemble leading researchers in the mid-IR fiber laser field to establish the collective state-of-the-art, including current fiber and fiber laser technological maturity; to assess the promise of mid-infrared fiber laser technology for supporting the future broad area situational awareness needs of NATO; to highlight the current issues and challenges; and to propose ways to advances the state of the art in mid-infrared fiber laser technology.

SUMMARY OF TALKS

1 – Richard Quimby, Worcester Polytechnic Institute, USA

Rare Earth Doped Non-Oxide Glasses for Mid-IR Fiber Lasers

Richard Quimby of Worcester Polytechnic Institute gave the opening presentation of the workshop, as one of the two keynote speakers. His presentation was split into four parts, first an overview of mid-IR rare earth transitions, then theory and experiment on non-radiative relaxation, following by a presentation of the fiber laser demonstrated to date and finally the modeling of fiber lasers.

After a short introduction on mid-IR fiber lasers, Prof. Quimby presented the upper limit on transition wavelength due to the optical transparency band of different glass hosts (selenide, sulfide, fluoride and oxide) and nonradiative quenching of the upper laser level (giving the rule of thumb: more than 5 photons to bridge the gap). This shows that nonoxide glass host is necessary for mid-IR laser operation.

The next part of his presentation concentrated on non-radiative relaxation in chalcogenide glasses, in order to determine if the energy gap law was still valid for this kind of material. Experimental results show that the slopes of the non-radiative decay rate as a function of the energy gap are similar for almost all rare-earth hosts expect sulfide glass. The multiphoton rate is determined from the calculated radiative decay and the fluorescence lifetime measurements and by varying the temperature. Measured extra non-radiative decay is likely due to energy transfer to localized vibrational modes. Then the author enumerated the different limiting factor to the performance of chalcogenide fiber laser:

1) Nonradiative quenching of upper laser level;
2) Excited state absorption;
3) Bottle-necking; and
4) Fiber attenuation.

In the third part of his presentation, Prof. Quimby reviewed the state of the art of chalcogenide lasing fiber. He referenced two published results, first an Er:ZBLAN fiber laser at 2.75 µm with 1.7 W output power; second, a Ho:ZBLAN fiber laser at 2.86 µm with 2.5 W output power. Both fibers were co-doped with Pr to reduce bottle-necking. But no fiber laser above 3 µm was reported, and no experimental rare-earth doped chalcogenide glass fiber laser has yet been demonstrated. For wavelength range 4.5-4.7 µm the possible candidate seems to be the ($^6H_{11/2} \rightarrow {}^6H_{13/2}$) transition of Dy^{3+}, utilizing the cascading lasing ($^6H_{13/2} \rightarrow {}^6H_{15/2}$) to avoid bottle necking.

The last part of this talk was devoted to the simulation of the all fiber cascaded scheme in the case of ($^6H_{11/2} \rightarrow {}^6H_{13/2}$) transition of Dy:GeAsGaSe at 4.6 µm. Measurements coupled with calculations of emission and absorption cross-section of the three transitions involved indicate that the optimum pump is at 1710 nm, and that the optimum intermediate wavelength is 3350 nm. Simulation shows that the lasing of the intermediate wavelength increases considerably the output power at 4.6µm especially at high pump power. He also noted that fiber loss must be kept under 3 dB/m to obtain efficient lasing between 4.2 and 4.6 µm (HSe impurities can be reduced by purifications techniques).

Prof. Quimby answered audience questions as to the damage threshold of his fiber, which was >2 $GWcm^{-2}$. He added that non-radiative decay does not lead to large heating and that the heat transfer is efficient because of the small fiber core.

2 – Markus Pollnau, University of Twente, The Netherlands

Mid-Infrared Lasers: Challenges Imposed by the Population Dynamics of the Gain System

Prof Pollnau gave an extensive talk on population dynamics of the gain media, focused on Er doped material. He first concentrated his presentation on the model he used, which is the central field approximation with perturbations. Then he described the different mechanisms that govern the gain media, including stimulated, spontaneous and interionic processes. As an example he showed that the decay from $^4I_{9/2}$ level of Er^{3+} due, in part, to multiphoton relaxation depends on the number of photon required to reach the lower level: 2 photons for oxide material $\tau = 0.5$ µs, 4 photons for fluoride $\tau = 7$ µs and 7 photons for chloride $\tau = 4$ ms.

The next part of the presentation dealt with the four-level scheme of the 3 µm Er laser, especially the importance of lower level depletion because of its longer lifetime ($\tau = 9$ ms) compared to the upper level ($\tau = 6.9$ ms). The processes that can help to deplete the lower level are ESA (Excited State Absorption), energy transfer, ETU (Energy Transfer Upconversion) and laser action. In ZBLAN fiber at low dopant concentration, ESA becomes stronger than GSA (Ground State Absorption) and ETU is not important because of large distance between ions. In order to simulate the population dynamics it is essential to know the ESA. Prof. Pollnau presented a technique to measure ESA cross-section. He gave results on pump and probe beam measurement of ESA at 800nm in ZBLAN:Er^{3+}. One result of this measurement is that the best pump wavelength is 792 nm.

The next part of this presentation was devoted to cascade-lasing regime. Prof. Polllnau showed that the slope efficiency of a ZBLAN fiber laser at 2.7 µm ($^4I_{11/2} \rightarrow {}^4I_{13/2}$) can be increased if the $^4S_{3/2}$ level is clamped to threshold inversion by ($^4S_{3/2} \rightarrow {}^4I_{9/2}$) 1.7 µm lasing, because the lower level of the 2.7 µm transition is not populated by the ($^4S_{3/2} \rightarrow {}^4I_{13/2}$) 850 nm pumping. Another way to increase the laser efficiency at 2.7 µm is to reduce the lower level lifetime relative to the upper level lifetime. This can be done by codoping the fiber with Pr^{3+}. Then the presentation considered highly doped ZBLAN fiber which favors ETU. Prof. Pollnau explained how the measurement of luminescence decay can help to determined ETU.

The following section discussed an energy-recycling regime where half of the ions in the lower laser level are upconverted and can participate in the laser transition at another time, leading to an increase in the efficiency by a factor two. Finally the thermal issue was tackled. The strong heat load is due to multiphoton relaxations after the ETU process. The use of cladding-pumped fiber with typical doping concentration of 8.10^{19} cm^{-3} reduces ESA and ETU, and exploitation of a cascading process at 1.6 µm diminishes other spectroscopic processes.

To conclude his talk Prof. Pollnau reviewed how the population dynamics of Er^{3+} (3 µm) fiber lasers depend on Er^{3+} concentration, pump parameters and fiber geometry. The experimental results that he obtained were (with increasing doping concentration):

1) Core pump, ESA → upper cascade lasing
2) Clad pump, codoping → lifetime quenching
3) Clad pump, ETU → energy recycling
4) Clad pump, laser depletion → lower cascade lasing

The current output power demonstrated is 9 W uncooled and 24 W cooled.

3 – Marcel Poulain, Université de Rennes / Le Verre Fluoré, France

Fluoride Fiber Sources: Problems and Prospects

Prof. Marcel Poulain from Rennes University and Le Verre Fluoré, France, presented the problems and prospects of fluoride glass fiber sources. After some comments on pioneering achievements, his talk first discussed fluoride glass technology and glass processing, and then detailed interesting rear earth transitions for producing mid-infrared output. Achievements are described in term of optical transmission and spectral range covered for different doped fiber lasers, as well as the performance of a supercontinuum source based on a ZBLAN fiber. Finally, problems and prospects of fluoride glass fiber sources were reviewed.

The first glass was discovered by chance in 1975. Most studies concentrated later on the fluorozirconates based on ZrF_4 and HfF_4, but also AlF_3, GaF_3 and InF_3 which have significant differences in chemical durability, glass stability, mechanical strength and hardness and phonon energy. Typical glass compositions and general physical properties were described and the vacancy model to describe the structure of the glass was discussed. The glass synthesis is based on several main steps including melting, refining, casting and annealing with consideration of specific features such as low melt viscosity, volatilization, devitrification and hydrolysis. Solutions to overcome the water action issue were recommended. The optical quality of samples was discussed in terms of different defect sources. As several parameters must be considered and optimized, manufacturing of optical quality glass samples is difficult and time consuming. Fiber manufacturing steps were outlined starting from powders and ending with finished fibers. A schematic representation of a fiber-tower was used to describe how fluoride glass fibers for the infrared are pulled from fluoride glass performs which is influenced by several parameters that have to be optimized.

The second part of Prof. Poulain's presentation sketched the general features of fluoride optical fibers and of rare earth doped fluoride fibers in particular, and gave examples of rear earth transitions in the mid-infrared spectral region. Typical mid-infrared optical transmission of multimode and single mode fiber were presented, and different fiber designs were listed. Pump transitions and laser transitions were also summarized for rare earths dopants in ZBLAN. It was also noted that, not onlyl has supercontinuum emission been achieved with ZBLAN fibers in laboratories, but systems are also commercially available. Various parameters such as the fiber length, the pump wavelength, etc. can be adjusted. Le Verre Fluoré has developed a commercialized supercontinuum source emitting from ~0.7 µm to ~4 µm

Issues concerning mechanical strength, material aging chemical durability and thermal stability of the fiber were then discussed. Key processes must become better understood to prevent fiber failure. To prevent liquid water from coming in contact with the glass surface, fibers are protected by coatings, jacketing, and cabling. Solutions to protect the end faces have also been developed, such that fluoride fibers have been in use in industrial environment for more than 10 years. Reliable gratings can be written into fiber by femtosecond lasers. The damage threshold is critical for high power lasers and supercontinuum generation, and recent experiments using femtosecond pulses suggest that the intrinsic damage threshold could be higher in ZBLAN than in silica. The sources of fiber defects have been identified, and the processing parameters must be adjusted to avoid them.

Future work will include extending the optical window by increasing the content of InF_3. Encouraging laboratory results have been obtained and developments are still in progress. The potential for photonic crystal fiber (PCF) is large and may be achieved with ZBLAN glass in future, but PCF seems to be more difficult to achieve with ZBLAN than with silica or chacogenide fibers. Due to ZBLAN's thermal properties, these PCF would offer extended possibilities.

4 – Mohammed Saad, IR Photonics, Canada

Development of Infrared Fibers in Canada

Dr. Mohammed Saad, from IRphotonics, Canada, provided an overview of infrared fiber development in Canada. After an overview of the company and its capabilities, his presentation dealt first with fluoride glass properties and fluoride glass fibers and the wavelength range achievable using these materials. Then he listed the optical and mechanical properties of those fibers and summarized latest achievements for high powers.

The overview of the fluoride glass families highlighted that hundreds of fluoride glass compositions exist but that only few can be drawn into commercial fibers. The best known are the fluorozirconate ZrF_4 (ZBLAN) and the new fluoroindate InF_3 whose transmission extends to longer infrared wavelengths than that of ZBLAN glass, up to 5.5 µm. The advantageous properties for fiber laser design were summarized. The homogeneity of glass properties, together with its great machinability and good surface roughness make it an ideal material for aspherical lenses for both the UV and the IR. Single point diamond turning allows realization of convex or concave ZBLAN substrates.

The fluoride fiber draw tower is similar to a silica fiber tower, but the drawing oven is quite different due to the lower softening temperature of fluorides, and the fiber diameter control is very challenging due to the important variation of viscosity with temperature. Examples of different realized designs were shown with single mode and multimode fibers. Coating possibilities together with stripping and cleaving capabilities were mentioned, and cleaved end faces of different fibers were shown. These fibers can be doped with a wide range of rare earth dopants such as Er, Pr, Tm, Dy, Ho, Yb, Nd, and Sm with dopant concentrations up to 100,000 ppm.

The origins of optical losses were identified and typical attenuation curves were shown for ZBLAN and InF_3 fibers in the mid-IR wavelength range, with attenuation losses varying from 0.03 dB/m to 0.003 dB/m for various ZBLAN fibres and 0.1 dB/m for InF_3 fibre. Splicing efficiency has been evaluated with ZBLAN multimode and single mode fibres and Bragg gratings have already been written using a femtosecond 800 nm laser.

High power fibres and high power connectors were designed and developed by IRphotonics for delivering high power laser beams in the mid infrared wavelength range. Results of transmissions tests were presented. Dr. Saad emphasized that fibres have to be optimized for each specific application, which requires a close collaboration between the fiber producers and the fiber users.

5 – Thomas Schreiber, Fraunhofer-Institut für Angewandte Optik und Feinmechanik, Germany

Scaling of Fiber Laser Systems Based on Novel Components and High Power Capable Packaging and Joining Technologies

A useable mid-IR source for IRCM requires not only fibers but also coupling and joining components. The packaging technologies are also critical for the whole fiber-based system to be useful for the intended application, especially outside of the carefully controlled environment of the laboratory. To this end, Dr. Thomas Schreiber, from Fraunhofer-Institut für Angewandte Optik und Feinmechanik, gave a presentation centered on novel components and high power capable packaging and joining technologies. After reviewing the packaging and joining technologies available, novel components and their potential were described. An example of a mid-IR source was discussed before suggesting possible further directions for improvement.

Joining technologies for optoelectronic packaging always imply the bonding of different optical components with or without macroscopic intermediate layer or media between both materials depending on their adhesion/cohesion fit. Each technology was explained with example technical realizations for illustration. Among the technologies with an intermediate layer, one can cite the adhesive bounding that was already successfully used for the alignment of a micro lens array to a CCD sensor, the laser soldering technology used for example for optics dedicated to lithography and the solder bumping allowing a fiber coupled diode achievement. Techniques such as mineralic bonding, direct bonding or laser based splicing or tapering do not need an intermediate layer and they permit for example, the splicing of end caps (($\varnothing$1500µm) onto a multimode fiber ($\varnothing$720µm) with very low optical losses.

6 – Curtis Menyuk, University of Maryland USA

Maximizing the Bandwidth from Supercontinuum Generation in Photonic Crystal Chalcogenide Fibers

The first speaker of day two, and the workshop's second keynote speaker, was Prof. Curtis R. Menyuk of University of Maryland (UMBC), USA. He presented a method to maximize the bandwidth of supercontinuum generation in photonic crystal chalcogenide fibers. This work is based on the PhD dissertation of Dr. Jonathan Hu (now at Princeton University), and was realized in collaboration with Dr. L. Brandon Shaw, Dr. J. S. Sanghera and Dr. I. D. Aggarwal, at the U.S. Naval Research Laboratory.

The goal of Prof. Menyuk's work is to make a broadband mid-IR source (2 - 10 µm) based on supercontinuum generation. Photonic crystal fibers (PCF) were often used for supercontinuum generation (PCF are fibers with small, regularly spaced air holes that go along the fiber). The reason is that a single mode propagates in PCFs over a broad wavelength range, and PCFs have an enhanced nonlinearity compared with conventional step index fibers. Moreover, the dispersion can be tailored in PCF to broaden the output bandwidth.

Dr. Menyuk presented work based on solid-core chalcogenide PCF (one hole is missing in the center of the fiber). Chalcogenide is a glass based on chalcogen (sulfides, selenides, tellurides) compounds with arsenide. The advantages to use chalcogenide instead of silica fiber are: the attenuation in silica grows rapidly beyond 2.5 µm, whereas in the chalcogenides, it remains small beyond 10 µm. Moreover, the Kerr nonlinearity is 1000 higher in chalcogenide than in silica fiber.

The design goal is to increase the maximum wavelength of the spectrum as rapidly as possible. Supercontinuum generation is a complicated process, using the Kerr nonlinearity, the Raman effect and the dispersion to broaden the bandwidth of an optical signal, but there are general design criteria that work well:

1) Design the fiber so that it is single-mode (increases the effective nonlinearity)
2) Ensure that four-wave mixing is phase-matched with the largest possible Stokes wavelength (Rapidly moves energy to a large wavelength)
3) Make the second zero dispersion wavelength as large as possible (Allows the soliton self-frequency shift to go to long wavelengths)

Prof.. Menyuk discussed modelling of supercontinuum generation in an As_2Se_3 fiber, with a five-ring hexagonal structure and a 2.5 µm pump wavelength. The fiber parameters to vary are the air-hole diameter d and the pitch Λ. The pulse parameters to vary are the peak power and the pulse duration. To solve the generalized nonlinear Schrödinger equation (GNLS) for a broad set of fiber and pulse parameters, different fiber quantities are needed. Some are experimentally determined (Kerr coefficient, Raman gain, material dispersion) and other are calculated (total Raman response, total dispersion). For the accuracy of the GNLS model, these parameters have to be accurately determined.

To validate the simulation, results were compared with experimental supercontinuum generation obtained in an As_2Se_3 PCF with one ring of air holes and a pump source at 2.5 µm (Shaw, *et al.,* Adv. Solid State Photonics, TuC5, 2005). The simulations accurately reproduce the bandwidth of the supercontinuum of 2.1 to 3.2 μm to within 5%. Thus, measured nonlinear response can completely account for the supercontinuum generation.

In the second part of his presentation, Dr. Menyuk applied this model to his example. He showed that a bandwidth of 4 µm can be generated using an As_2Se_3 photonic crystal fiber with $d / \Lambda = 0.4$ and $\Lambda = 3$ µm at a 2.5 µm pump wavelength. Validation of the overall design approach shows it to be a useful tool for maximizing the supercontinuum bandwidth in chalcogenide fibers. This approach can be applied to a wide variety of chalcogenide fibers (Weiblen, *et al.,* As_2S_3 fiber, presented at CLEO 2010).

7 – Dan Hewak, Optoelectronics Research Centre, University of Southampton, UK

Chalcogenide Glass for Active and Passive Mid-IR Applications

Dr. Dan Hewak presented a quick overview of the Optoelectronic Research Centre. Then his presentation was divided in three parts, first chemical background on chalcogenides, then optical fiber development, and finally mid-IR devices.

Dr. Hewak highlighted the capabilities at the University of Southampton, and summarized the basics of chalcogenide synthesis. He reminded the audience that bad luck can be turned into opportunities. Thus the total destruction of the laboratory in 2005 forced researchers to return to basic theory and modelling, giving them the chance to to prepare many future experiments in the eventual new facilities.

Dr. Hewak pointed out that the quality of starting materials is of major concern, illustrating this with eloquent pictures of contrasting results obtained using raw materials from two different suppliers. Contact between water and chalcogenide must be avoided, as illustrated by the extreme sensitivity of powder samples to atmosphere exposure. The improvement in fiber attenuation achieved between 1995 and 2001 by taking care of impurities attests to how critical this is.

In outlining fiber development, Dr. Hewak described the chemical vapor deposition (CVD) technique, showing good results of reducing impurities. Measured loss values in GLS (Ga:La:S) are still higher than what is predicted, but these fibers still show an order of magnitude lower attenuation (2-3 dB/m) than commercial arsenic based fiber. A comparison of multiphonon decay rates in oxide, fluoride and chalcogenide glasses, shows that this gives the edge in optical efficiency to the chalcogenides. Chalcogenide glasses can cover the entire spectral range from 3-5 µm, with lasing output depending on the doping material.

An important part of Dr. Hewak's presentation dealt with doped glass microspheres. He first explained how to prepare and sort them, and then explained the characterization process. The diameter of the spheres ranges from 500 nm to 500 µm. Their fluorescence spectrum has two peaks centered at 900 nm and 1080 nm. Lasing was obtained in the microspheres with a pump threshold of 82 mW. Interestingly, squeezing the spheres appears to improve their performance.

The last topic of this presentation concerned nanophotonics, especially active plamonics and metamaterials. The concept behind active plasmonics is to switch between transparent and opaque waveguide composed of GLS. GLS could, in principle, be switched between amorphous and crystalline form by applying an optical or electrical field. A metamaterial composed of GLS might be useful as an electro-optic modulator. This device would have a transmission contrast of 4:1 and could be adjusted across VIS-IR by design.

8 – Daniel Creeden, BAE Systems, USA

Silica Fiber Lasers and Amplifiers as Pump Sources for Frequency Generation

Daniel Creeden from BAE Systems, USA, gave a very informative talk on silica fiber lasers and amplifiers as pump sources for nonlinear frequency conversion devices. After an overview of nonlinear frequency conversion, this talk consisted of three parts: the first dedicated to a general fiber overview, the second dealing with the design constraints and limitations due to non linear effects in fiber, and the third addressing considerations for fiber doped with rear earths such as Yb, Er, Er:Yb and Tm and used in nonlinear conversion. In closing, Dr. Creeden pointed out that more emphasis needs to be placed on component and fiber development to be able to develop fiber sources without free-space coupling.

The overview on nonlinear conversion summarized the needs for mid-IR generation in terms of pump sources and nonlinear materials. Common nonlinear materials were reviewed (PPLN, ZGP, OPGaAs) along with the typical fiber dopants available for mid-IR pumping (Er, Yb, Er:Yb, Tm and Tm:Ho). Dr. Creeden also compared a bulk crystal laser pump scheme with a fiber based pump scheme.

Fiber systems face limitations when scaling the pulse energy, to include self-focusing, surface and bulk damage, unwanted nonlinear effects, and amplified spontaneous emission. These were reviewed along with preferred mitigation strategies. Despite these limitations, silica fiber systems give access to high average power with diffraction limited performance; and operate at high repetition rate with high efficiency, far better than diode-pumped solid state lasers. Due to the excellent beam quality that they provide, the wavelength agility that they offer and the pulse width and PRF agility available, they are the perfect pump source for frequency conversion. In addition, the fiber technology allows splicing the fibers together to eliminate free-space transitions.

Dr. Creeden then presented details on Yb- and Er:Yb-doped fiber systems used in pumping PPLN; and Tm- and Tm:Ho-codoped fiber systems well suited for pumping ZGP and OPGaAs. For each rare-earth doped-fiber, the advantages, disadvantages, challenges, and special fiber design considerations were described in detail, and resulting properties were listed. Set-up and performance of state-of-the-art fiber lasers or fiber amplifiers were presented and nonlinear frequency conversion results were detailed. These included:

- A PPLN OPO pumped by a pulsed Er:Yb fiber amplifier
- A mid-IR ZGP OPO pumped by a Tm-doped fiber amplifier
- A mid-IR OPGaAs OPO pumped by Tm,Ho-codoped fiber laser

The general issues that should be addressed concerning the components and the fiber geometries were discussed. Dr. Creeden suggested that efforts should concentrate on promising Tm and Tm:Ho fiber development for mid-IR generation, because of their high efficiency and wavelength advantages. He also emphasized the need for components and fiber developments especially to eliminate free-space coupling in future fiber systems, allowing systems that are completely optically confined.

THE PANEL DISCUSSION

At the end of the workshop, Dr. Ishwar Aggarwal (U.S. Naval Research Laboratory) moderated a discussion among the speakers and participants. The highlights are summarized below.

Which are the main IR laser applications?

IRCM, as well as other military applications such as ranging, medical, aerospace applications.

Depending on the application we need either to produce a very broadband IR spectrum, or a very narrow one.

What are the most limiting factors for mid-IR fiber lasers?

- Packaging
- Maturity of the fiber gain or nonlinear media
- Availability and maturity of the necessary pump sources

Cost of fiber development is high and can't be supported entirely by the fiber developer. It seems that the fiber suppliers face the challenge of a suspicious marketplace, and must debunk the false negative impression that fibers for the mid-infrared (non-silica fiber) suffer from moisture. A first lasing demonstration should be achieved, even with some bulk components in the design, to prove the promise of mid-infrared fiber laser technology.

The development of chalcogenide fiber faces as yet some issues and challenges. Although non-doped chacolgenide fibers are stable, the rare earth doped material suffers from instabilities. It is also challenging to write gratings in these fibers.

Pump sources emitting at 1.4 µm and 1.7 µm seem also to be an issue because they do not have adequate brightness or efficiency, their cost is high. Efficient Q-switched 2 µm fiber lasers have been demonstrated and can be considered as efficient pump sources. In addition, they are already farther in the infrared in wavelength than more commonplace Yb-based fibers. Practical pump sources emitting at 3µm already are also desirable. Réal Vallée of Laval University reported a7 W CW 3 µm source, but it should be operated in pulsed mode to be efficient for pumping.

Le Verre Fluoré mentioned an ongoing project to develop hollow core fiber filled with gas and pumped at 2 µm, but the cost of such development is high.

CONCLUSION

The promise of mid-infrared fiber laser technology was highlighted by all the invited speakers and also during the panel discussions by the attendees. Issues and challenges have been listed for the fibers themselves as well as for coupling components and enabling technologies like fiber Bragg gratings. Progress in many of the areas discussed has been noteworthy and encouraging in recent years, and should be continued in the future.