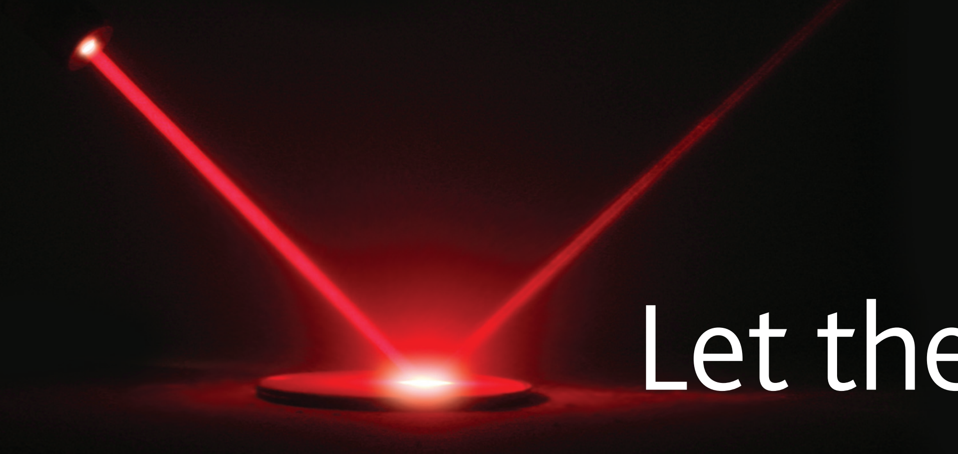


Let there be light

Dr Sergey Mirov discusses the 15 years of pioneering research that led to his project on transition metal (TM) doped crystalline lasers and the new frontiers this technology is crossing

To begin, could you outline the main aims and objectives of your research?

Middle-infrared (mid-IR) laser sources operating over the 'molecular fingerprint' 2-15 μm spectral range are in great demand for a variety of applications including molecular spectroscopy, non-invasive medical diagnostics, industrial process control, environmental monitoring, atmospheric sensing and free space communication, oil prospecting, and numerous defence-related applications. Mid-IR wavelengths are usually generated using relatively complex nonlinear optical conversion techniques or by means of direct generation in hetero-junction lead-salt, antimonide, or quantum cascade semiconductor lasers featuring limited output power and tuning range. Impurity doped crystalline lasers constitute another viable route for mid-IR coherent sources.

Can you explain the meaning of a doped II-VI structure?

Let us first clarify the basic concept of our approach and its major differences with regards to semiconductor diode (including ZnSe visible diode laser) or quantum cascade lasers (QCLs). Energy transfer from the electrically excited II-VI semiconductor host to the transition metal impurity, resulting in the formation of a population inversion, along with lasing on the impurity transitions, represents the major difference between the proposed lasers and conventional semiconductor and QCLs; where stimulated photons are emitted through the recombination of electron-hole pairs across the material band gap (conventional semiconductor lasers), or through the use of intersubband transitions in a repeated stack of semiconductor multiple quantum well heterostructures (QCLs). This difference in the mechanism of lasing differentiates the proposed TM:II-VI lasers from conventional semiconductor and QCL lasers and enables energy storage capability, as well as an increase in lasing bandwidth by up to two orders of magnitude. The current project is unique, because it provides understanding of new pathways for future electrically pumped broadly tunable mid-IR lasers.

What is the significance of electrically pumped laser realization based on transition metal (TM) doped II-VI structures?

There are two major advantages of our systems in comparison with semiconductor and QCL lasers.

The first one is in a transformative improvement in the bandwidth and in much broader (more than one octave) tunability. A large gain bandwidth enables development of either ultra-broadly tunable lasers for sensing application or design systems for ultra-short pulses generation. The second advantage of the proposed systems could be in much higher output energy in comparison with semiconductor lasers. Finally the obvious advantage of electrically pumped lasers based on TM doped II-VI structures in comparison with solid state lasers is in more convenient direct electrical excitation.

How is your work developing this nascent technology? What will be the benefits of the technology?

Since initial breakthroughs in 1996 at Lawrence Livermore National Lab, USA, progress in chromium and iron doped II-VI lasers achieved by several research groups made them the laser sources of choice when one needs a compact system with tunability over 1.9-6 μm. Continuous wave (CW) output powers exceeding 20W, joule level of output pulse energies and efficiencies up to 70 per cent, have been demonstrated in several optically pumped Chromium and iron doped semiconductors. The unique combination of technological (low-cost ceramic material) and spectroscopic characteristics makes these materials ideal candidates for optically pumped mid-IR tunable laser systems. In addition to effective mid-IR lasing under optical (diode or fiber laser) excitation transition metal doped II-VI media, being wide band semiconductors, hold potential for direct electrical excitation. The main goal of our research programme was to develop a new type of electrically pumped lasers combining unique features of impurity doped crystalline lasers with engineering capability of semiconductor lasers to be pumped directly by electrical current.

Why is many-body luminescence from highly excited quantum-confined structures is a conceptually important topic?

For successful realisation of electrical excitation, two conditions should be satisfied; the efficacious and sustainable excitation of the crystal host by electrical current, and the efficient energy transfer from the host to the mid-IR lasing TM impurity. The second condition can be achieved either via carrier impact energy transfer or via recombination processes in bulk and especially in quantum confined structures. The reasons for the enhancement of energy transfer rate in quantum confined structures are that first, quantum size confinement should increase the oscillator strength of the free exciton due to an increase of the electron-hole overlap factor. Secondly, the oscillator strength of the exciton bounded to the impurity centre depends on the oscillator strength of the free exciton and electron-hole exchange interaction term which is also supposed to be large due to the carrier's confinement. Thus, we may expect a large enhancement in the oscillator strength of an exciton bound to an impurity ion embedded in a quantum confined structure.

Tuning **in**

Researchers at the **University of Alabama at Birmingham** have been producing infrared laser technology with unprecedented tunability, and now their work is nearing commercial availability

MID-INFRARED (mid-IR) LASERS have a large number of important applications, providing their wavelength is sufficiently flexible for sensing purposes. The lasers are able to offer medical, environmental, scientific and counter-terrorism applications, including the detection of explosives, chemical and biological warfare agents and their precursors. They are also useful in industrial process control, and the measurement of medically important molecular compounds in the exhaled breath of patients. The new technology, which uses transition metal (TM) impurities embedded within semiconductors, moves beyond the capabilities of currently available products. Against semiconductor lasers, or quantum cascade laser technology, the new laser structure is set to provide a far greater flexibility in usage. There are significant improvements in bandwidth, as well as broader tunability, excellent for sensing applications, and also ultra-short pulse generation. There is also the possibility of a significantly higher output energy than available in semiconductor lasers. In comparison with solid state lasers, the obvious advantage of electrically pumped lasers based on TM doped II-VI structures is in more convenient direct electrical excitation.

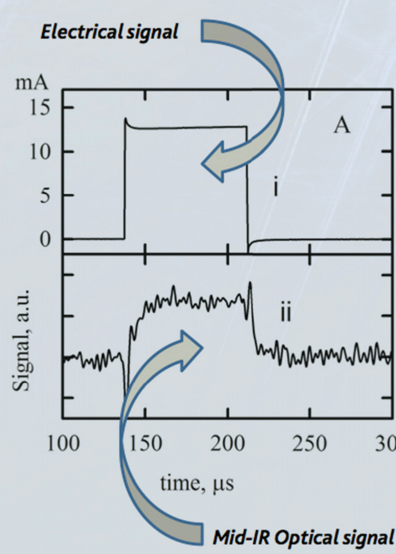
The team at the University of Alabama at Birmingham is investigating the possible approaches for advancing this form of lasers, hoping to press forward with this technology based on iron, cobalt and chromium dopants.

Attempting to produce a laser which can provide an extended range of wavelengths and powers has been an extremely challenging task, however the group has been able to make a number of significant breakthroughs in their work. They have already developed an efficient technology for post-growth doping of a number of crystals, providing a low-loss, uniformly doped gain material, as well as an option for hot pressing of TM doped II-VI powders directly into the laser ceramic. They have pioneered the first chromium-zinc sulphide and chromium-zinc selenide microchips, and have also demonstrated a gain switched room temperature iron-zinc selenide mid-IR laser. The lasers with chromium ions have achieved over a 20W output at a real efficiency of over 50 per cent. There have been a large number of other innovations, but a major part of the team's success has been the adoption of their technology by a commercial supplier. TM doped II-VI gain media, and multiple mid-IR tunable lasers have now become commercially available from a partner organisation, IPG Photonics Corporation. The technology is now set to go from strength to strength, with the team's innovative research working alongside the commercial production of lasers, research and commercial interests operating in synergy.

APPROACHING INNOVATION

The development of products is testament to the researcher's hard work, yet they did not set out to produce commercially available lasers. Dr Sergey Mirov, who is leading the study, instigated the project: "Initially, we worked for pure scientific interest, studying new and interesting aspects of solid state physics, but in the course of research it became clear for us that transition metal doped II-VI lasers combine the versatility of the ion-doped solid-state lasers with the engineering capabilities of semiconductor lasers". As they continued their work, the researchers were able to see that their approach was leading towards the production of electrically pumped lasers with unprecedented bandwidth in the mid-IR part of the spectrum. At this point, the drive for the potential applications of such a system of lasers, or commercialisation meant that the research built momentum, working towards the position which the team is now in. Aiming for the numerous potential applications in the

FIGURE 1. OSCILLOSCOPE TRACES OF THE ELECTRICAL CURRENT ACROSS THE AL:CR:ZNSE SAMPLE (i) AND THE MID IR OPTICAL SIGNAL (ii)



The technology is now set to go from strength to strength, with the team's innovative research working alongside the commercial production of lasers, research and commercial interests operating in synergy

detection and mitigation of health and safety hazards, the researchers were driven forward in their work. Through their continuing investigations they are now able to move towards the creation of commercial optically pumped and future workable electrically pumped products.

DEVELOPING PROCESSES

One of the major hurdles in creating a commercially viable technology has been progressing beyond previous fabrication methods. The process of Czochralski growth, a method for the doping of crystals using transition metals, requires the application of high pressure and temperature in order to prevent the sublimation of transition compounds. Consequently, Czochralski growth is of questionable commercial viability, particularly for mass production, and the researchers have been forced to develop their own techniques. They have worked with II-VI polycrystalline passive materials to develop quantitative post-growth thermal diffusion, imbuing the structures with TM ions in a fast thermo-diffusion process, providing uniform doping up to 7 mm within the crystals, and featuring low scattering loss. The patented technology is at the heart of all high energy records of tunable solid state mid-IR lasers which utilise transition metals, which ensures a consistently high optical quality of fabricated thermo-diffusion doped crystals. Mirov understands the importance of this innovation for their work: "It is certain that this technology was a first step in the direction of developing a laser media for optically and electrically pumped mid-IR tunable lasers". It is hoped that the work of the team will continue to pioneer new methods and technologies, further enhancing their position as leaders in their field.

OVERCOMING OPPOSITION

These achievements have worked against the prevailing attitude of the industry, something which has begun to cause the group problems as they move towards commercialisation. Chromium and iron have traditionally been considered ineffective for luminescence in visible semiconductor diode applications, which has made it extremely difficult for the researchers to find semiconductor fabrication plants that are willing to assist in the creation of their designs, and also holds them back in

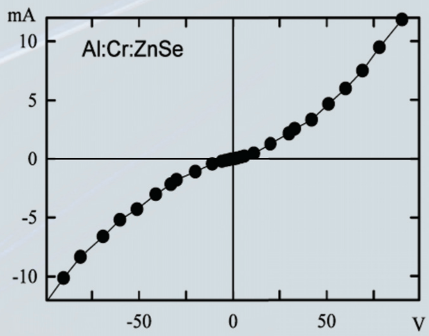


FIGURE 2. ELECTRICAL CHARACTERISATION OF AL:CR:ZNSE SAMPLE

their industrial collaborations. The work which they must now complete is in increasing the efficiency of the energy transfer between the excited host and the TM ions. Their present research examines the process of direct impact excitation of TM ions by electrical carriers, yet this is currently less than 1 per cent efficient. However, this may change through the development of doped quantum confined, quantum dot or quantum well lasers, which would be able to confine the semiconductor exciton near or immediately at the TM ions. This would provide a marked increase in the energy transfer process, providing more efficient lasers. Still in its early stages, the group is hoping to continue pushing this line of enquiry, opening up new approaches through their investigation.

COLLABORATIVE APPROACHES

Advancements made through this research have only been possible with the diligent work of a large number of scientists, engineers and graduate fellows. The work of Mirov has been matched by Dr Vladimir Fedorov, Dr Dmitry Martyshkin and Dr Renato Camata, as well as 11 current and former graduate fellows. There have also been useful collaborations with a number of members of IPG Photonics, who have been at the forefront of readying the technology for market. The hard work of the involved project members has been backed by generous financial support, some from IPG Photonics Corporation themselves, and some provided by the National Science Foundation and the United States Air Force. Through the combined funding, assistance and diligence of this large group of people, this investigation has been able to produce signigicant results, pushing forward the possibilities of mid-IR lasers and bringing them to a marketable position.

INTELLIGENCE

NEW CLASS OF BROADLY TUNABLE MIDDLE-INFRARED ELECTRICALLY PUMPED SOLID-STATE LASERS

OBJECTIVES

Comprehensive study of the mechanisms of carriers' TM ions energy transfer due to carrier impact and recombination in bulk and quantum confined structures. Design, fabrication, and characterisation of TM doped II-VI structures for electroluminescence and laser studies. Comprehensive studies and optimisation of lasing characteristics of electrically pumped TM-doped II-VI structures.

KEY COLLABORATORS

Vladimir Fedorov, **Igor Moskalev**, **Dmitry Martyshkin**, **Mike Mirov and Renato Camata**

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SERGEY MIROV received his PhD in Physics in 1983, from the P N Lebedev Physics Institute of the USSR Academy of Sciences, Moscow. He was awarded the USSR First National Prize for Young Scientists in 1982, for the development of LiF colour centre saturable absorbers. Mirov has been a faculty member at the Department of Physics, UAB since 1993 and is currently a University Professor of Physics at the University. He also holds the position of Director at the Center for Optical Sensors and Spectroscopies. He is 2009 Caroline P and Charles W Ireland Prize recipient for Scholarly Distinction. Dr Mirov is a Fellow of the Optical Society of America, and member of the American Physics Society, and SPIE. He has authored or co-authored over 350 scientific publications in the field of quantum electronics, has published a book, several book chapters, and holds 18 patents.

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