Fabrication of Three-Dimensional Chiral Photonic Circuits and Electro-Optical Devices in Silica Using Femtosecond Ultrafast Lasers

Kevin P. Chen
Department of Electrical and Computer Engineering, University of Pittsburgh, Pittsburgh, PA 15090, USA. E-mail:kchen@engr.pitt.edu

ABSTRACT:

This report summarizes the international collaborative research under the IREE program carried out in the Optical Fiber Technology Center (OFTC) at the University of Sydney, Australia. Microstructured optical fibers are emerging photonic devices with potential to revitalize the entire fiber optical industry. Using photonic bandgap structure, light can be confined in both hollow and pure silica fiber cores without the need of dopant to increase the refractive index of the fiber core. However, these fibers present uniques challenges for the laser fabrication of fiber grating since pure fused silica has very weak photosensitivity. Teaming up with researchers in the OFTC, both vacuum ultra-violet and ultrafast laser have been used to induce fiber grating in pure silica core air-hole microstructured fibers. Grating inscribed in the pure silica core exhibit excellent high-temperature stability. Fiber Bragg gratings in air-hole microstructured fibers have been successfully inscribed in various air-hole microstructured fiber for sensing applications. In addition, Pitt's researchers also worked with OFTC's scientists on fiber poling research and design and packaging microstructured fiber devices.

INTRODUCTION

This IREE program is a supplement program to the NSF award titled "GOALI:Fabrication of Three-Dimensional Chiral Photonic Circuits and Electro-Optical Devices in Silica Using Femtosecond Ultrafast Lasers." This IREE program was made to the University of Pittsburgh on September 2006.

The objective of the original NSF award is to develop a novel laser processing technique to fabricate high-quality and low-cost lightwave circuits and electro-optic devices in silica glasses. By taking advantage of multi-photon processes driven by femtosecond laser pulses, novel three-dimensional photonic devices and electro-optical devices (poling) will be fabricated in silica glasses with feature sizes below the diffraction limit.

Although the NSF program carried out on the campus of the University of Pittsburgh has been progressed well, our research can be fundamentally enhanced by an extensive access of state-of-the-art of laser fabrication facilities, ample supplies of microstructured fiber samples, and open communications with a large number of experters and researchers in the field. This IREE program provided such opportunities.

Our host institute, the Optical Fiber Technology Center (OFTC) at the University of Sydney is one of the world leading centers on laser fabrication of glass photonic devices (photosensitivity), glass poling, and microstructured fiber optics. The IREE program

enables us to establish a strategic alliance with this world-class photonic center. This has no doubt enhanced the current NSF award and also produced profound influence to the R&D careers of our IREE students.

The photosensitivity and poling research on our NSF program requires extensive access to fiber manufacturing facilities for specialty fiber samples. Although these facilities are commercially available, the high service fee forbids the extensive use of such facilities. The proposed international collaboration with the OFTC solved this problem. The IREE collaboration with the OFTC not only secures our source of specialty fiber samples, but also provides the University of Pittsburgh researchers hands-on experience in manufacturing specialty fibers using OFTC's fiber draw towers. Our NSF program also requires extensive access of various laser fabrication facilities. The collaboration with the OFTC dramatically expanded our research capability in fiber grating fabrication and glass poling. Most importantly, this IREE program offers an eye opening experience to our students. Our graduate students have chance to interact with world-class researchers on a daily basis. The eye witness account, the hand-to-hand interaction, and hallway chat with these experts changed the perspective of our graduate students on their own research.

The OFTC is well known for its pioneering work on the laser fabrication of gratings, photonic crystal fibers, and extensive applications in fiber sensing, fiber lasers, and fiber optical telecommunications. There are three fiber draw towers in the institute where photonic crystal fiber is drawn. Two gratings laboratories equipped with a frequency-doublt argon ion laser and an ArF 193-nm excimer heres are used to write gratings and carry out photosensitive works. The laboratories have about 20 phase masks and a fully automatic interferometric grating writing setup. All these state-of-the-art facilities were made available for this IREE collaboration at no additional cost.

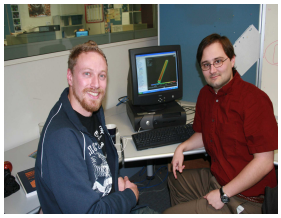
During the summer of 2007, Ph.D student Charles Jewart and the NSF PI Kevin P. Chen visited the OFTC. The student stayed in the OFTC for a period of three month (June to August, 2007) to carry out FBG writing using various UV and ultrafast laser systems. The PI spent one month (June 2007) to help the experiment and communicate with various researchers in the institute. We expect to visit the OFTC again next year.

RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

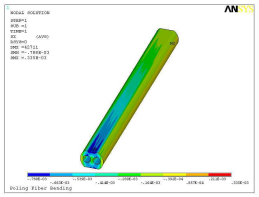
The original plan of research carried out during this IREE program is two foldeds: 1) we planned to utlize the state-of-the art fiber Bragg grating writing facilities in the OFTC to produce fiber Bragg grating in microstructured fibers for sensing applications; 2) we will develop close research collaboration with the glass poling group headed by Dr. Simon Fleming.

Both research collaborations are directly connected with the current NSF award. At the University of Pittsburgh, we have carried out very active research on 3D photonic circuit fabrication in glass using MHz ultrafast laser, this research is progressing well due to the adequent facility support and comprehensive past research experience. However our students face a lot of challenge on the proposed the poling research due to lack of appropriate hand-on experience. The collaboration with Dr. Simon Fleming, a world

renowned scholar on the glass poling research has dramatically enhanced our poling research program. We now started a two-prone approach on poling research. Existing waveguides written at the University of Pittsburgh using a MHz ultrafast laser has been sent to the OFTC for post thermal poing studies using their unique second-harmonic optical microscopy. At the same time, the existing poling experimental setup from the OFTC is transplanted to the University of Pittsburgh. We will perform an in-situ poling studies during ultrafast laser wrting of waveguides. Poled samples from both the OFTC and Pitt will be compared for their 2nd order nonlinearity, structure modifications, and guided optical charateristics changes. During the month-long stay, the PI has worked with a senior research fellow at the OFTC Dr. Honglin An to learn the entire poling process. This expertise has now being transferred to the PI's graduate student Ben McMillen to perform in-situ poling research during ultrafast laser writing.



(a)

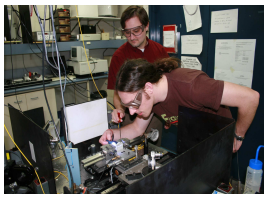


(b)

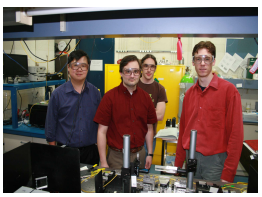
Fig. 1: (a) Pitt graduate Chuck Jewart (right) help OFTC graduate student Philip Hambley on Finite Element Analysis (FEA) of stress distribution in microstructured fiber. (b) Stress distribution of double-flat twin-hole fiber under bending.

Our interaction with OFTC researchers also generated mutual benefit. During the IREE visit, Pitt's graduate student Charles Jewart has aided the specialty fiber design works using a finite element analysis [1] shown in Fig. 1a. Mr. Jewart's simulation work has helped the design and packaging of two-hole fiber electro-optical voltage sensors. During this collaboration, Jewart remotely loginned in Pitt's computer facility to build FEA model and perform stress analysis on various air-hole microstructured fibers under various winding configuration (e.g. Fig. 1b). By performing such analysis, OFTC researcher has gained better understanding of the torsion of two-hole fiber during winding. The longevity of fiber packaging and offset of sensor reading can therefore be predicted and corrected.

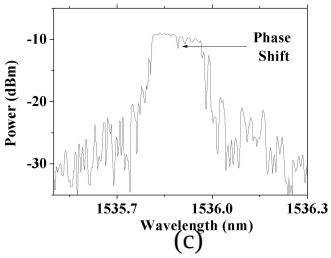
On the other hand, Pitt researchers benefit directly from OFTC's fiber Bragg grating writing expertise. We gained unrestricted access to OFTC's 244-nm and 193-nm fiber Bragg grating writing facilities. We have placed our focus on the fabrication of precise phase-shift grating using both lasers. With the help of OFTC, we now are ready to build our own laser writing setup to perform this precise fabrication at Pitt. Fig. 2a shows the Pitt's research Chuck Jewart and OFTC research Michael Stevenson's collaborative experiment on phase-shift grating writing. The transmission spectra of a typical phase shift FBG is shown in Fig. 2c.



(a)



(b)



(c)

BROADER IMPACTS OF THE INTERNATIONAL TRAVEL

Since both PI and the IREE graduate student (Chuck Jewart) are not unrepresentative minority or female, the year one trip doesn't involve the promotion of diversity. However, the IREE program offers both PI and the graduate student (US citizen) an eye opening experience. We have both interacted with over a dozen of world-renown scientists and engineers in fiber optics (Fig. 3).

Fig. 3: Farewell picture taken before the departure of the PI. From left to right: Mattias Åslund, Philip Hambley, Andrew Michie, Chuck Jewart (Pitt), Michael Stevenson, Kevin P. Chen (Pitt), Alexandra Pohl, and Nathaniel Groothoff.

From the PI's perspective, this IREE trip dramatically expands the PI's research capability in laser processing and fiber optics. We gain two immediately advantages from this visit beyond our original plan of poling and photosensitivity research. First, we have secured a variety of air-hole microstructured fiber samples which are otherwise unattainable given the current program budget. These invaluable fiber samples will enable the PI to carry out a wide-array of interesting experiments. Second, we embarked a new research direction on active distributed feedback fiber laser sensing in microstructured fiber. By implementing air-hole structure in Er-doped fiber and measuring polarization mode beating in RF-regime, we are now developing the most sensitive fiber sensors in the world. On a broader perspective, the knowledge, experiment-know-how, and professional friendship gained from this IREE trip will enable the PI to perform a far more ambitious research program in fiber optics and laser processing. In addtion, the PI had a chance to learn the research funding mechanism in Australia, this will enable the PI to carry out a more effective research collaboratioin internationally to further the PI's career.

The IREE student Chuck Jewart is a US citizen. Before this trip, he has never stepped out the US border. This international experience has no doubt changed his perspective of the world. He has a chance to learn the world-class work hand-by-hand. He was able to perform experiment together with highly experience scientists. The IREE program gave him an opportunity he would had to gain in top-notch schools or labs such

as Stanford or the Bell lab. The expertise he gained from Pitt was also put into immediate use to help OFTC researchers. His technical competence enables him to make many professional friends, an asset will last for long time for his future professional development.

DISCUSSION AND SUMMARY (LIMIT: 1 PAGE)

This IREE program was a supplement award to the PI's DMI award titled "GOALI: Fabrication of three-dimensional chiral photonic circuits and electro-optical devices in silica using femtosecond ultrafast lasers". Three most significant achievements is list as following:

- Establish a strong tie with Dr. Simon Fleming's group at the OFTC on poling research. This trip leads to a direct transplant of the poling experiment expertise to Pitt. The establishment of this collaboration has direct impact on the current NSF program.
- Working with Dr. John Canning's group, we have successfully fabricated fiber Bragg grating at 785 nm, and phase shift grating for DFB lasers. We will use ultrafast laser at Pitt to trim the phase shift to eliminate the polarization beating [2], another direct benefit for the current NSF program.
- This trip expands the PI's research capability on micro-structured fiber sensing. The IREE program allows us to access a wide array of microstructured fibers at no cost. The collaboration with the OFTC has generated a new research direction for the PI: ultra-high sensitivity distribuited feedback laser sensor array in Er-doped microstructured fibers.
- PI and his student have helped the OFTC researcher on microstructured fiber design for their R&D effort toward noval twin-hole fiber voltage sensors. Using the finite element analysis, we have performed stress analysis on various two-hole fiber with double-flat, single-flat, and circular outer surfaces. The stress contour under bending of those fibers will provide OFTC researcher guidance on fiber device packaging.

Overall, we found the IREE program is an extremely useful add-on to the current NSF program. Although US currently run the most competitive and all-round research in the world, many other developed or developing countries also have their own research strength. The IREE program allows US researchers to leverage the reputation of the NSF and the United State as a country to tap into this resource at very low cost. This leverage becomes extremely valuable for researchers from second-tier Univesities like Pitts. Funded by the NSF, IREE researchers do not compete with international counterparts on their own research funding, promotion, and other administrative concerns. This allows a much more open collaborations, dialogs, and wide access of research facilities in international research institutes. This is a true win-win scenario.

As a recommendation to IREE program, I feel IREE program should actively identify a number of institutes in the world such Canadian NRC and Japan's RIKEN for IREE collaborations. It will be great if NSF can set up liason office to enhance these connections.

ACKNOWLEDGEMENTS

This IREE program is a supplement of a NSF award **0556086,** GOALI: Fabrication of three-dimensional chiral photonic circuits and electro-optical devices in silica using femtosecond ultrafast lasers. We appreciate the support of program manager Dr. Mary Lynn Realff.

We gratefully thank Dr. Simon Fleming, Dr. Honglin An, Dr. John Canning, Mr. Andrew Michie, Dr. Alexandre Pohl, Dr. Mattias L Åslund, Mr. Nathaniel Groothoff, Mr. Michael Stevenson, Dr. Stuart Jackson, and Mr. Philip Hambley at OFTC, who offer us productive and pleasant IREE experience.

REFERENCES (INCLUDE IF RELEVANT; SAMPLES BELOW)

1. C. Jewart, K. P. Chen, B. McMillen, M. Bails, S. P. Levitan, J. Canning, and I. V. Avdeev, "*Sensitivity Enhancement of fiber Bragg gratings to transverse stress using microstructure fibers***"**, *Opt. Lett.*, vol. 31, pp. 2260-2262, 2006

2. H. Storoy, B. Sahlgren, R. Stubbe, "*Single polarisation fibre DFB laser*", Electron. Lett., vol. 33, pp. 56-58, 1997

BRIEF BIOGRAPHIES OF RESEARCHERS

Kevin P. Chen received the B.Sc. degree in Control Science and Physics from Xiamen University in China in 1994. He received his Ph.D. degrees in Electrical Engineering from University of Toronto in 2002. Since 2002, he has been an Assistant Professor of Electrica and Computer Engineering at the University of Pittsburgh. He has more than 70 refereed publications since 2000 in fiber optics, ultrafast laser processing, sensors and actuators, and nuclear micro-engineering. He is a Paul E. Lego faculty fellow at the University of Pittsburgh and a recipeient of NSF CAREER award.

Chuck Jewart is a PhD student at the University of Pittsburgh. He participated in this IREE program. He received both B.Sc. and M.Sc. dgrees in Electrical Engineering in 2005 and 2006 respectively, all from the University of Pittsburgh. Chuck carries out his PhD research in fiber optical sensing with a focus on microstructured fiber devices. He has published six journal papers.