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14. ABSTRACT We optimize the properties and fabrication process of fiber Bragg gratings for sensors and for stabilization of semiconductor lasers. We investigate the effects of boron and titanium doping on thermal sensitivity. We find that gratings written through the polymer coating are stable to high-intensity infrared light traveling in the core of the fiber. These gratings are designed for wavelength locking of semiconductor lasers used for pumping erbium-doped fiber amplifiers. We find that hydrogen-loaded fibers have reduced mechanical strength compared to fiber gratings written without hydrogen. We also investigate the effect of thermal annealing on the strength of fiber gratings. We find that annealing at 230 degrees C slightly improves the fiber's mechanical strength, while annealing hydrogen-loaded fibers decreases the fiber's mechanical strength. Bending sensitivity of gratings is measured.

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FINAL TECHNICAL REPORT

Final technical Report:0002AC for the period 01 Sept 1999 to 31 Oct 2000

Project Title: (STTR Phase II) "Novel Fabrication of Ultra-strong Thermally Stable Gratings through the Coating of Optical Fibers with UV Light"

Program Manager: Dr. Howard Schlossberg

Contract number: F49620-99-C-0059

Principal Investigator: Dr. Dmitry Starodubov

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Change of Objectives: None

Patents filed: None

New Discoveries or Inventions: None

Fabrication of Ultrastrong Fiber Bragg Gratings Written Through the Polymer Coating of Optical Fibers

The purpose of the STTR program is to help small companies get started and become commercially successful. This STTR grant has been enormously successful not only in that it has enabled D-STAR Technologies, Inc. to produce valuable scientific results, but it has enabled the company to establish itself, obtain external funding, and grow into a modest-sized company. This STTR grant to D-STAR Technologies, Inc. allowed it to grow from a company of 4 people in a rented laboratory into a thriving company of 40 people (at this writing) with its own 12,500 square foot production facility in Long Beach, California.

D-Star Technologies, Inc. is now shipping products in quantity to customers. Its gain-flattening filters are also being designed into the products of first-tier companies in Italy, England, and the United States. Its pump stabilizing gratings written through the fiber's polymer coating will make their commercial debut this summer.

A short history:

D-Star Technologies, Inc. was formed in 1998 by Prof. Jack Feinberg and Dr. Dmitry Starodubov with a quarter million dollars of "angel" funding from Ortel Corporation (now part of Agere). D-STAR received a Phase I STTR grant from the AFOSR in the Fall of 1998, and a Phase II grant for $0.5M from the AFOSR in the Fall of 1999. In August of 2000 D-STAR completed its first round of funding for $5M from Redpoint Ventures, a venture capital firm with offices in Los Angeles and Menlo Park. D-STAR leased a 12,500 square foot production facility in Long Beach, California and began production of fiber optic components in January, 2001. Sales for the first 3 months total $0.5M. The expected revenue for the calendar year 2001 is $10M.

D-STAR Technologies, Inc. makes components for fiber optic amplifiers. Specifically, D-STAR makes gain-flattening filters based on long-period gratings. Also, D-STAR Technologies, Inc. has patented a novel technology for writing Bragg gratings through the coatings of optical fibers. These gratings are ideal for pump stabilizers and especially for submarine applications, where mechanical strength and reliability are key issues. The physics of writing these pump stabilizing gratings in optical fibers was the focus of this STTR project.

Below we summarize the principal scientific achievements of this STTR project.

Principle scientific achievements:

1) Optimization of fabrication of fiber gratings written through polymer coatings.
2) Determined grating stability under light exposure.
3) Determined grating reliability under mechanical stress.
4) Determined design constrains for Bragg gratings for locking pump lasers.

1) Optimization of fabrication of fiber gratings written through polymer coatings in fibers with no hydrogen loading

We optimized the properties and fabrication process of fiber Bragg gratings for two applications: i) sensors and ii) stabilization of semiconductor lasers. Issues of fiber design, grating properties and grating reliability were addressed.

Gratings written in different fibers were compared for thermal sensitivity. We tested gratings written in high-NA fiber, a fiber having a Ti-doped cladding layer, and boron co-doped fiber. The high-NA fiber is manufactured by Fibercore, Ltd. (England), and is used by the US Navy in their towed sensor arrays. The fiber with 7% Ti in the cladding is designed to have a very low thermal expansion of the cladding. The fiber with a high boron concentration is used to make gratings for stabilizing 980-nm semiconductor lasers.

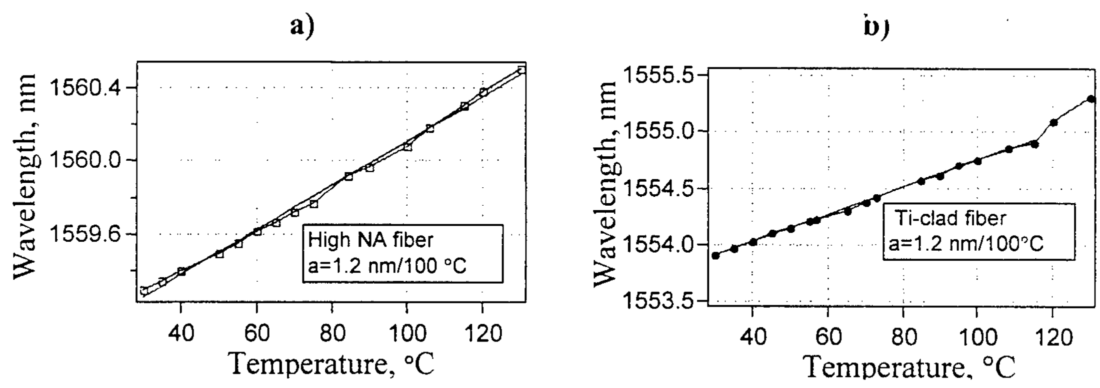

Figure 1. Thermal sensitivity of fiber Bragg gratings in a) high-NA fiber for sensor arrays and b) fiber with Ti-doped cladding having a zero thermal expansion coefficient. The similarity of the slopes (the coefficient labeled "a" in the inset) of the two plots shows that the cladding's thermal expansion has a negligible effect on the grating's thermal sensitivity.

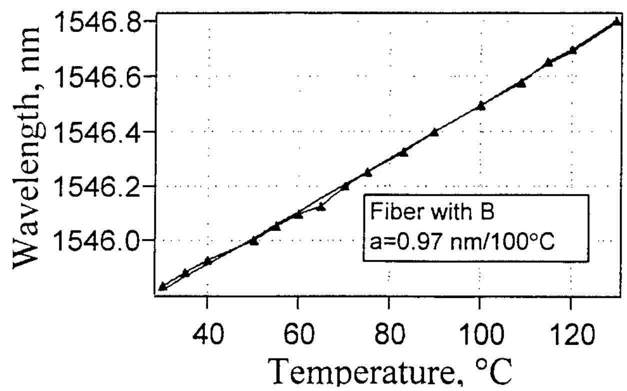

Figure 2. Thermal sensitivity (the "a" coefficient in the inset above) is reduced by ~20% in a fiber with a high concentration of boron.

Figure 1 shows that reducing the thermal expansion of the cladding did not improve the thermal properties of fiber gratings written in the fiber core. However, Fig. 2 shows that in the fiber with B codoping there was a ~20% decrease in the grating's thermal sensitivity, making gratings written in this fiber thermally more stable and therefore more suitable for locking pump lasers.

2) Grating stability under light exposure

We also tested the stability of the gratings written through the polymer to high-intensity infrared light traveling in the core of the fiber. The gratings under the test are designed for wavelength locking of semiconductor lasers used for pumping erbium-doped fiber amplifiers.

Intense light at 1.06 microns from an ancient but powerful cw Nd:YAG laser (Coherent Antares) was launched into the fiber containing a Bragg grating. The 400 mW of IR power exceeded that available from pump lasers presently on the market. (The typical power of a pump laser at 980 nm is 100-200 mW.) Figure 3 shows that the reflectivity of the fiber grating didn't change even after 500 J of IR energy. There was a barely resolvable shift in the grating wavelength by 0.1 nm to shorter wavelengths. This shift could be caused by erasure of any unstable, uniform portion of the grating, because this would alter the refractive index and thereby change the resonance wavelength of the grating.

The stability of these gratings to high IR energies makes them suitable for the commercial application of stabilizing the output of high-power semiconductor laser sources.

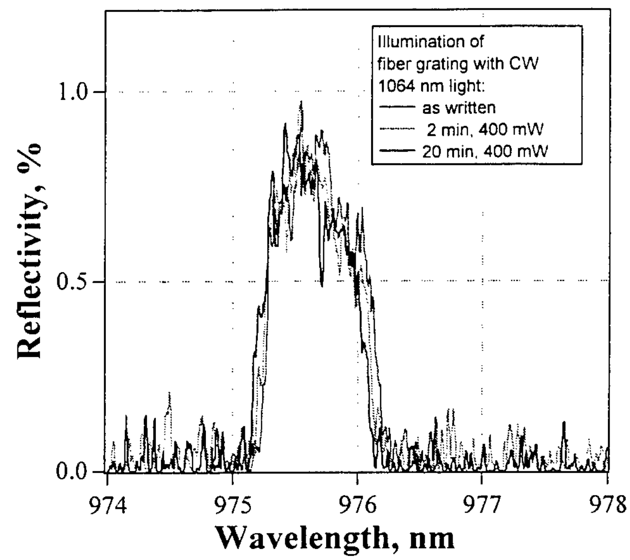

Figure 3. High-intensity infrared exposure of a fiber Bragg grating written through the polymer does not change the grating's properties.

3) Grating reliability under mechanical stress

We also investigated the effect of thermal annealing on the strength of fiber gratings. The polymer-coated fibers were heated for 1 min and then tested on a commercial proof tester manufactured by Vytran.

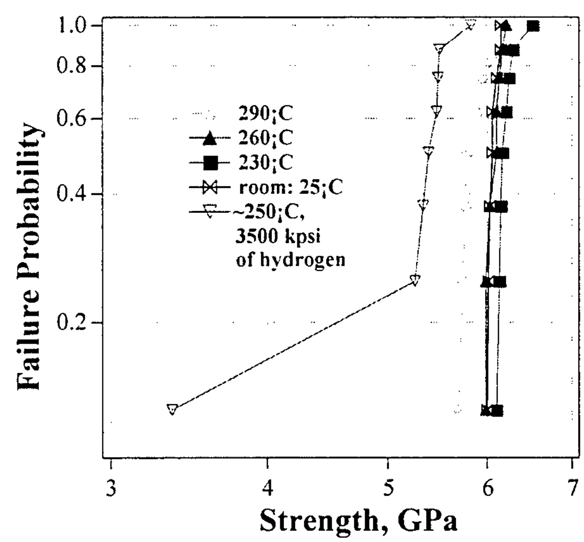

Figure 4. High-temperature annealing (up to 260°C) of ordinary fiber gratings does not degrade their mechanical strength. However high-temperature annealing of hydrogen-loaded fibers does cause a significant degradation of mechanical strength.

Figure 4 shows that heating the fiber to 230°C slightly improved the fiber strength. This was probably due to a decrease in the relative humidity and a drying of the polymer coating. (Water markedly decreases a fiber's strength.) Further heating of the fiber to 290°C caused the fiber's strength to decrease only slightly, possibly due to reactions of the fiber's coating with fiber's silica surface. However, hydrogen-loaded fibers showed a marked decrease of strength after annealing. For this reason we have decided to avoid high-temperature annealing and hydrogen loading of fibers in our grating production facility.

4) Design constrains for Bragg gratings for locking pump lasers

We asked several manufacturers of pump laser to give us their requirements for gratings to stabilize their lasers. Gratings for pump stabilization should have a bandwidth between 0.3 nm and 1 nm, and a reflectivity in the range of 1% to 7%. From the uncertainty principle, for a uniform fiber Bragg grating a bandwidth of 0.5 nm requires a grating length of about 1 mm at 980 nm. However, a 1-mm long grating would have a maximum reflectivity below 0.5% for a grating written through polymer fiber coating. This is because the polymer coating limits the total fluence of UV light that can reach the fiber core, which limits the achievable core index modulation to approximately 10^{-4}.

In order to make fiber gratings with a larger reflectivity we must use a different design. Instead of using very short gratings to produce the required bandwidth, we can use chirped gratings. A chirped grating can produce the required bandwidth and reflectivity. The trade off is that the grating is longer, typically a cm or so. A concern of such long fiber Bragg gratings is their sensitivity to bending. Therefore, we studied the sensitivity of our longer gratings to mechanical bending, and the results are shown in Fig. 5. We were able to bend our gratings down to a 6-mm radius without a noticeable change in the grating spectrum. The telecom requirement is a 16-mm bending radius.

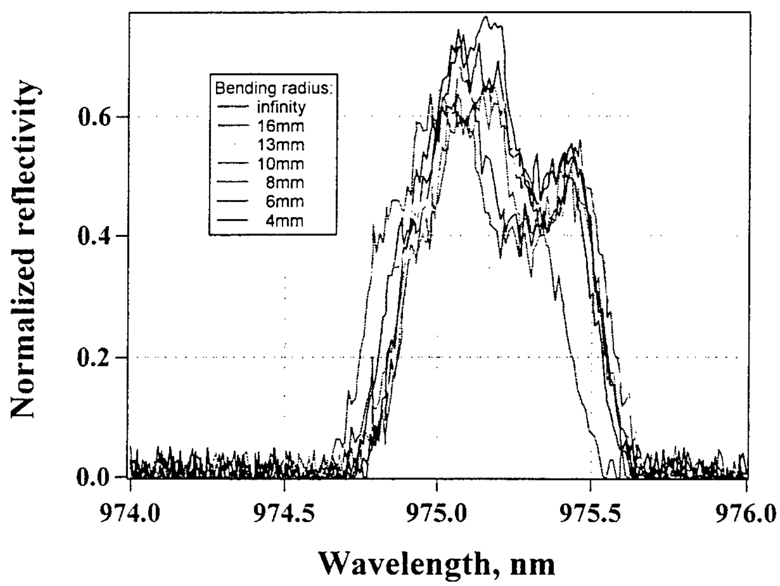

Figure 5. Bending of fiber Bragg gratings written through the polymer coating. The grating resonance is relatively immune to bending down to a 6-mm radius. The grating reflectivity is 2% and its length is 2 cm.

- In our next set of experiments, we fabricated fiber Bragg gratings designed for 1480-nm pump lasers. These gratings required a bandwidth of ~2 nm and a reflectivity of ~5%. Figure 6 shows an example of a fiber grating for the 1480-nm wavelength range written through fiber's polymer coating. This grating was written in a fiber having a boron co-doped core. The main drawback of B co-doped fibers for 1480-nm applications are their relatively high absorption (~0.2dB/m) in the 1480-nm range). Fibers doped only with Ge to the required numerical aperture (N.A. = 0.13) are not sensitive enough. Further optimization of the fiber composition is required.

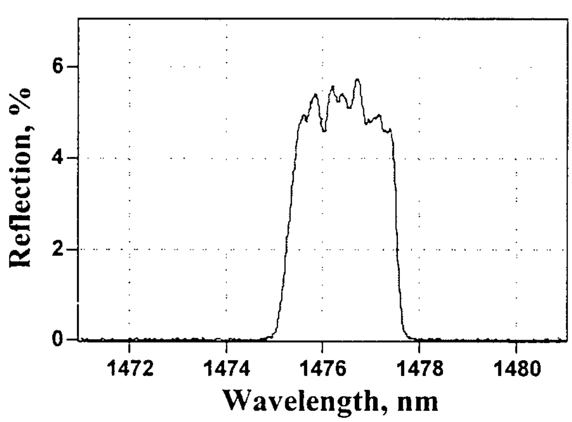

Figure 6. A Bragg-grating resonance in the 1480-nm wavelength range formed in a B-co-doped fiber through the fiber's polymer coating.

Publications:

Results from this STTR project were presented November 6, 2000 at the "Photonics East" conference in Boston Massachusetts. Dr. Dmitry Starodubov, the Principal Investigator of this STTR project, taught a short course entitled, "Fiber Gratings for WDM Applications." Relevant viewgraphs from that course are attached to this report.

Inventions:

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