

# LONG PERIOD GRATINGS AS FLOW SENSORS FOR LIQUID COMPOSITE MOLDING

Sylvia R. M. Kueh<sup>1</sup>, Richard S. Parnas<sup>2</sup>, Joy P. Dunkers<sup>2</sup>, Suresh G. Advani<sup>1</sup>, Paige S. Furrows<sup>3</sup>, Mark E. Jones<sup>3</sup>, Timothy A. Bailey<sup>3</sup>

<sup>1</sup>Department of Mechanical Engineering, University of Delaware, Newark, DE 19716-3140

<sup>2</sup>Polymers Division, NIST, 100 Bureau Drive, Gaithersburg, MD 20899-8543

<sup>3</sup>F&S/Luna Innovations, P.O. Box 11704, Blacksburg, VA 24062-1704

## ABSTRACT

One of the most important issues in liquid composite molding (LCM) is the complete saturation of the preform by the resin to eliminate voids or dry spots in the structure which could later adversely affect the structural integrity of the part. While there have been efforts in developing reliable mold filling simulations for LCM, very few successful flow sensing systems exist for detecting actual resin arrival during mold filling. In this study, the feasibility of using optical fibers with long period gratings (LPG) as sensors for monitoring flow in the LCM process was investigated. An advantage of using LPGs is that they are more robust and less susceptible to background noise than simple bare fibers. Furthermore, the location of resin arrival can be easily identified as the signals from each LPG uniquely correspond to predetermined wavelengths along the source spectrum. The LPGs are sensitive to changes in the refractive index and register a strong signal change when covered with resin. In this study, the LPG sensors were placed in the middle of a preform stack inside a mold and the sensor response after the mold was properly closed, and when the resin covered a particular LPG was monitored. An assortment of preforms, which included random mats and unidirectional fabrics, with a series of fiber volume fractions were used to determine their effects on the sensor response.

**Keywords:** Flow sensing system, long period gratings (LPG), liquid composite molding (LCM)

## 1. INTRODUCTION

Since the late 1970's, it has been discovered that exposing a section of a germanium-doped optical fiber to an interference pattern of UV light results in a spatial modulation of the refractive index with the same spacing [1-2]. Long period gratings (LPGs) are fabricated by transversely exposing the side of such a fiber through an amplitude mask with a desired grating period [1,3-4]. The long period describes a fiber refractive index perturbation with a periodicity that is much greater than the wavelength of light. In most cases, this is on the order of hundreds of micrometers.

The periodic index changes couple light from a guided fundamental mode in the core of single-mode fibers to a co-propagating cladding mode [3,5-10]. Only certain wavelengths are converted to the cladding modes and subsequently attenuated while others pass unaffected through the gratings. These are manifested as "dips" in the transmission spectrum. Wavelengths at which a LPG couples light is determined by the grating period and the difference between the two modal refractive indices [1,3,8,11-12]. Due to their wavelength selective attenuation properties, LPGs have primarily been employed as spectral filters in fiber optic communications systems [1,3,6-8,10,12-15].

Since the cladding modes interact with the material surrounding the cladding, LPG spectral responses are modified by changes in the properties of the ambient condition, in addition to any modulation of the core and cladding guiding properties [1,6,12,15]. It is this characteristic that researchers have utilized to monitor changes in physical parameters such as stress, strain, temperature and refractive index [3,5-6,8,11,16-17] as well as chemical processes like corrosion monitoring [8] and biosensing [1].

In liquid composite molding (LCM), the fiber preforms are placed in a steel mold, which is then closed and resin is injected to saturate the empty pores in the preforms. However, under these typical manufacturing circumstances, it is difficult to "see" if the resin is fulfilling its function. Embedded sensors can help monitor the impregnation process and many such developments have been attempted [18-25]. For the first time, LPGs will be used as embedded flow monitoring sensors in LCM, to detect the arrival of resin in the mold during filling. When the higher indexed resin covers a LPG sensor, the light

that would have been attenuated gets coupled back into the core and, hence, there is no corresponding dip in the transmission spectrum. Such information would be very useful to composites manufacturers by alerting them to specific problems that could occur during resin injection.

Although the many currently existing simulation packages concerned with mold filling [26-31] have contributed tremendously in providing insight and understanding of this process, the design optimizations based on them have traditionally been conducted offline. This poses a difficulty when unanticipated anomalies are encountered during manufacturing. Moreover, the variations in the processing parameters are too numerous to be accounted for in these simulations. A more effective approach would be to monitor the progression of the mold filling as it is occurs and implement appropriate corrective measures as necessary online as well. We believe LPGs have the potential to serve in such a sensory capacity.

LPGs possess the usual advantages associated with fiber optic systems, for instance small size and light weight, which allows them to be embedded without compromising the host's structural integrity. Furthermore, their inherent immunity to electromagnetic interference gives these systems a clear edge over other flow sensing systems that are based on the resin dielectric properties [22-25]. Moreover, LPG sensors have an additional advantage over other intensity-based fiber optic systems [18] in that they are robust to fluctuations in light amplitude due to unquantified connection losses and fluctuating light sources [19-21]. As each LPG sensor is uniquely wavelength encoded, several of them can be multiplexed on a single strand of fiber, and thereby minimizing the degree of additional heterogeneity introduced into the process.

As an initial step towards establishing the feasibility of using LPGs in such a capacity, experiments were conducted to benchmark the performance of LPGs under realistic composites manufacturing conditions. These tests included ascertaining the effects of fiber architecture and volume fraction on the sensor response. The results are presented here along with a brief comparison of simulated responses from LPG-based sensing system and continuous linear sensors.

## **2. EXPERIMENTAL SETUP AND PROCEDURE**

The LPGs were prepared at F&S on communication-grade optical fiber with a cladding diameter of 125  $\mu\text{m}$ . Each strand of fiber used had two 2.0 cm LPGs spaced 5.0 cm apart. The core refractive index is 1.4515 while the buffer refractive index is 1.444.

These optical fibers are sandwiched in between equal number of layers of fiber glass preforms and placed inside a flat plaque mold 1.0 cm x 15.2 cm x 22.9 cm with a transparent top as shown in Figure 1. The resin was injected from the same location as the optical fiber's point of entry into the mold. An environmentally friendly corn syrup-water mixture was used as the simulated resin having viscosities ranging from 0.3 Pa·s to 0.6 Pa·s. The refractive index of the simulated resin was higher than that of the cladding refractive index.

Both ends of the optical fiber are connected to the input-output ports of the Lunascan device using bare fiber adapters. The device is basically an optical spectrum analyzer (OSA) and light source. One port emits light at 1550 nm while the other collects and analyzes the optical spectrum transmitted through the fiber. The spectral output is displayed on a computer and only the spectrum of light between 1495 nm and 1585 nm is viewed using this system. Approximately three scans are taken by the system every second. Every spectrum that is recorded is the mean of several consecutive scans logged by the OSA. Averaging the scans ensures that any inherent fluctuations in the system are accounted for.

A spectrum from the optical fiber is recorded before the fiber is placed inside the stack of preforms. It is also logged after the mold is closed, before the liquid is injected into the mold, and at various other times during the mold filling process. This procedure was done for random fiber mats, plain bi-directional weave and two cases of unidirectional fibers. In one case, the reinforcing fibers are parallel to the optical fiber alignment and transverse to it in the other case. Three fiber volume fractions were used for each reinforcing architecture. Table 1 summarizes the tests that were conducted. The check marks indicate the experiments that were conducted in this investigation.

## **3. RESULTS AND DISCUSSION**

The OSA system proved to be a fairly stable system since there was very little fluctuation (less than 0.004 standard uncertainty in relative intensity) in the scans obtained for each case. Figure 2 shows a typical spectrum of an optical fiber with two LPGs written on it. The vertical axis is relative intensity with respect to the maximum intensity detected by the

system for that particular scan. In this case, the LPGs were written such that light at 1509 nm and 1549 nm would be filtered out, as evident from the transmission dips seen in that figure.

These dips disappear when the simulated resin covers the sensor, coupling the light at that wavelength back into the core-propagating mode. When both LPGs are covered, the spectrum is like that of an optical fiber without any LPGs written on it. Since each of the LPGs is written at distinctly different wavelengths, it is possible to identify where and when the sensors are covered.

As with any optical fiber system, the LPGs are extremely sensitive to microbending when they are compressed between the preform layers inside the mold as can be seen in Figure 3. It was observed that signal deterioration worsened at higher fiber volume fractions and it was noticeably worst in the random mat case. There was the least signal deterioration with the parallel unidirectional reinforcements. Both the transverse unidirectional mat and bi-directional weave cases are between these two extremes, with the signals from the bi-directional weave being slightly more affected than the other.

It is possible that this deterioration in signal is due to a combination of effects. Not only is there excessive microbending on the optical fibers when it is compressed in the midst of the preform stack but the LPGs are also in intimate contact with the fiber glass reinforcement which has a similar refractive index as the buffer and cladding. Moreover, it is likely that compressive stresses are induced in the optical fiber itself.

The greatest challenge in these experiments was to retain the integrity of the sensor signals. To overcome this issue, a hollow glass sleeve was placed over the sensors. These protective sleeves have an inner diameter of 445  $\mu\text{m}$  and an outer diameter of 650  $\mu\text{m}$ . They are 4 cm long each, long enough to cover the entire length of the LPG and allow for some slight translational movement along the optical fiber during placement in the mold. These glass sleeves are not permanently fixed onto optical fiber so that liquid may flow inside them and reach the LPGs.

As can be seen from Figure 4 there is a slight difference between the signals from a LPG compressed inside a stack of random mats but is covered by such a sleeve and that of an uncompressed LPG. However, this is a vast improvement over the signals obtained when the sensor is not protected by the glass sleeve and is subjected to the same conditions inside the mold. When the resin simulant is injected into the mold, the dips disappear, as expected, after the resin simulant completely covers each LPG as is shown in Figure 5. However, this usually occurs after the flow front is observed to have moved beyond the sensor locations.

Although we have managed to isolate the source of the signal deterioration, using the protective glass sleeves on the LPGs is only an interim solution to the problem. Not only do they delay the resin from reaching the sensors, they are also significantly larger than the reinforcement fibers and the optical fiber itself. Hence, their presence in the mold might also affect the resin flow progression. Alternative solutions are being sought to retain the sensor's signal integrity without adding to the heterogeneity inside the mold.

#### **4. SENSOR PLACEMENT**

With the confidence that the LPGs will adequately function as flow sensors in a mold filling situation, the next step is to decide on their optimal location in the mold. This may be accomplished by applying an evaluation procedure similar to that discussed in [32], which assigns a score reflecting the relative performance of each sensor configuration considered. Although this algorithm was developed for sensors with continuous linear response, it could be modified in this case. to account for the discrete nature of the LPG response.

Just as the trajectory of the line sensor that performed the best in [32] was located in the top half of the mold, the best sensor location for a single LPG sensor is expected to be somewhere in that region of the mold as well. Moreover, it is expected that the score for this singular sensor will be less than that for the continuous linear sensor. In fact, adding more sensing points along a trajectory should improve the score since a set of strategically placed discrete sensors would yield more information about the mold filling process than just one. For example, a system with two sensing locations should outperform a system with just one. A more detailed account of this work will be included in an upcoming paper.

#### **5. CONCLUDING REMARKS**

It has been demonstrated that these LPGs can feasibly be used as flow sensors in a mold filling application. Their simple “yes/no” response to the presence of resin at a certain location makes them more robust and less susceptible to losses and fluctuations in light than intensity-based optical fiber sensors. Resin arrival is easily identified since each LPG can be fabricated to uniquely correspond to predetermined wavelengths along the transmission spectrum. This also allows the implementation of wavelength multiplexing along the same strand of fiber.

Although we were able to maintain most of the LPG signals, by using the glass sleeves, even while it was compressed in between fiber glass reinforcements in the mold, the sleeves were found to delay the sensor response. Efforts are still underway to find alternative solutions to this problem without increasing the complexity within the mold.

## 6. REFERENCES

1. Tran, T. A., Bhatia, V., D'Alberto, T., Murphy, K. A. and Claus, R. O., “Real-time Immunoassays Using Fiber-optic Long-period Grating Sensors”, *Society of Photo-Optical Instrumentation and Engineering V. 2676*, p165-170, 1996
2. Morey, W., “Distributed Fibre Grating Sensors”, *Proceedings of the 7th Optical Fibre Sensors*, p285–288, 1990
3. Vengsarkar, A. M., “Long-period Fiber Gratings Shape Optical Spectra”, *Laser Focus World V. 32*, No. 6, p243–37, 1996
4. Davis, D. D., Gaylord, T. K., Glyntsis, E. N., Kosinski, S. G., Mettler, S. C. and Vengsarkar, A. M., “Long-period Fibre Grating Fabrication with Focused CO<sub>2</sub> Laser Pulses”, *Electronics Letters, V. 34*, No. 3, p302-303, 1998
5. Du, W., Tao, X. M., Tam, H. Y. and Choy, C. L., “Fundamentals and Applications of Optical Fiber Bragg Grating Sensors to Textile Structural Composites”, *Composite Structures V. 42*, No. 3p217-229, 1998
6. Bhatia, V., D'Alberto, T., Murphy, K. A., Claus, R. O. and Nemanich, C. P., “Comparison of Optical Fiber Long-period and Bragg Grating Sensors”, *Society of Photo-Optical Instrumentation and Engineering: Smart Structures and Materials 1996: Smart Sensing, Processing, and Instrumentation, V. 2718*, p110–121, 1996
7. Vengsarkar, A. M., Pedrazzani, J. R., Judkins, J. B., Lemaire, P. J., Bergano, N. S. and Davidson, C. R., “Long-period Fiber-grating-based Gain Equalizers”, *Optics Letters, V. 21*, No. 5, p336 – 338, 1996
8. Greene, J. A., Jones, M. E., Tran, T. A., Murphy, K. A., Schindler, P. M., Bhatia, V., May, R. G., Sherrer, D. W. and Claus, R. O., “Grating-based Optical-fiber-based Corrosion Sensors”, *Society of Photo-Optical Instrumentation and Engineering: Smart Sensing, Processing and Instrumentation, V. 2718*, p170–174, 1996
9. Kosinski, S. G. and Vengsarkar, A. M., “Splicer-based Long-period Fiber Gratings”, *Proceedings of the 1998 Optical Fiber Communication Conference, V. 8*, p278–279, 1998
10. Lawson, R. C. and Safaai-Jazi, S., “Spectral Properties of Multiple Grating Structures”, *Proceedings of the 1997 IEEE SOUTHEASTCON*, p26–28, 1997
11. Henriksson, A., Sandgren, S. and Asseh, A., “Temperature Insensitivity of a Fiber Optic Bragg Grating Sensor”, *Society of Photo-Optical Instrumentation and Engineering, V. 2839*, p20–33, 1996
12. Lee, B. H. and Nishii, J., “Cladding-Surrounding Interface Insensitive Long-period Grating”, *Electronics Letters, V. 34*, No. 11, p1129–1130, 1998
13. Eggleton, B. J., Krug, P. A., Poladian, L. and Ouellette, F., “Long Periodic Superstructure Bragg Gratings in Optical Fibres”, *Electronic Letters, V. 30*, No. 19, p1620–1622, 1994
14. Fuchs, A. and Sung, N.-H., “Composite Interphase Study by Evanescent Fiberoptic Fluorescence”, *ANTEC '95, V. 53*, p2437–2441, 1995
15. Vengsarkar, A. M., Lemaire, P. J., Judkins, J. B., Bhatia, V., Erdogan, T. and Sipe, J. E., “Long-period Fiber Gratings as Band-rejection Filters”, *Journal of Lightwave Technology, V. 14*, No. 1, p58–65, 1996
16. Patrick, H. J., Williams, G. M., Kersey, A. D., Pedrazzani, J. R. and Vengsarkar, A. M., “Hybrid Fiber Bragg Grating/LongPeriod Fiber Grating Sensor for Strain/Temperature Discrimination”, *IEEE Photonics Technology Letters, V. 8*, No. 9, p1223–1225, 1996
17. Song, M., Lee, S. B., Choi, S. S. and Lee, B., “Simultaneous Strain and Temperature Sensing Using Two Fiber Bragg Gratings Embedded in a Glass Tube”, *Proceedings of the 1997 Conference on Lasers and Electro-Optics, CLEO, V. 11*, p392, 1997
18. Bernstein, J. R. and Wagner, J. W., “Fiber Optic Sensors for Use in Monitoring Flow Front in Vacuum Resin Transfer Molding Processes”, *Review of Scientific Instrumentation, V. 68*, No. 5, p2156-2157, 1997
19. Du, W., Tao, X. M., Tam, H. Y. and Choy, C. L., “Fundamentals and Applications of Optical Fiber Bragg Grating Sensors to Textile Structural Composites”, *Composite Structures, V. 42*, No. 3, p217-229, 1998
20. Foote, P. D., “Optical Fibre Bragg Grating Sensors for Aerospace Smart Structures”, *Proceedings of the Optical Fibre Bragg Grating Sensors for Aerospace Smart Structures, V. 17*, p14/1-14/6, 1995

21. Greene, J. A., Jones, M. E., Tran, T. A., Murphy, K. A., Schindler, P. M., Bhatia, V., May, R. G., Sherrer, D. W. and Claus, R. O., "Grating-based Optical-fiber-based Corrosion Sensors", Society of Photo-Optical Instrumentation and Engineering: Smart Sensing, Processing and Instrumentation, V. 2718, p170-174, 1996
22. Kikuchi, A., Higuerey, E. and Coulter, J., "An Experimental Investigation of Resin Flow Sensing During Molding Processes", Proceedings of the ASME MD (HTD) Advances in Computer-Aided Engineering (CAE) of Polymer Processing, V. 49, No. 1, p86-93, 1995
23. Kranbuehl, D., Kingsley, P., Hart, S., Loos, A., Hasko, G. and Dexter, B., "Sensor-model Prediction, Monitoring and In-situ Control of Liquid RTM Advanced Fiber Architecture Composite Processing", Proceedings of the 37th International SAMPE Symposium and Exhibition, V. 37, p907-913, 1992
24. Milovich, D., "Dielectric Resin Flow Sensing as an Aid to RTM Process Development", Proceedings of the 41st Sagamore Army Materials Research Conference, p365-376, 1994
25. Walsh, S. M. and Charmchi, M., "Free-surface Flow Observations in the Resin Transfer Molding (RTM) Process", Proceedings of the ASME HTD Heat and Mass Transfer in Materials Processing and Manufacturing, V. 261, p147-156, 1993
26. Bruschke, M. V. and Advani, S. G., "A Finite Element/Control Volume Approach to Mold Filling in Anisotropic Porous Media", Polymer Composites, V. 11, No. 6, p398-405, 1990
27. Demirci, H. H. and Coulter, J. P., "Intelligent Control of Resin Transfer Molding Processes (RTM) Utilizing Neural Networks and Nonlinear Optimization Methods", Proceedings of the ASME MD Processing, Design and Performance of Composite Materials, V. 52, p13-28, 1994
28. Han, K., Lee, L. J., Nakamura, S., Shafi, S. and White, D., "Dry Spot Formation and Changes in Liquid Composite Molding: II -- Modeling and Simulation", Journal of Composite Materials, V. 30, No. 13, p1475-1493, 1996
29. Lin, M. and Hahn, H. T., "A Robust and Efficient Approach for RTM Simulation", Proceedings of the ASME MD Advanced Materials: Development, Characterization, Processing and Mechanical Behavior; V. 74, No. 1, p71-81, 1993
30. Phelan Jr., F. R., "Flow Simulation of the Resin Transfer Molding Process", Proceedings of the 7th Technical Conference of the American Society for Composites, p374-380, 1996
31. Trochu, F., Gauvin, R., Gao, D. M. and Boudreault, J., "RTMFLOT - An Integrated Software Environment for the Computer Simulation of the Resin Transfer Molding Process", Journal of Reinforced Plastics and Composites, V. 13, p407-416, 1980
32. Kueh, S. R. M., Advani, S. G. and Parnas, R. S., "Virtual Sensor Simulation Study of Flow During Resin Transfer Molding Process", Proceedings of the 13th Annual ASC Technical Conference on Composite Materials, p 744 – 760, 1998

## 7. TABLES AND FIGURES

Table 1: Summary of tests that were conducted

Architecture Type	Fiber Volume Fraction (%)	Dry	With Liquid Injection	Without Hollow Core	With Hollow Core
Random mat	9	√	√	√	√
	13				
	17				
Unidirectional (parallel)	50	√	√	√	√
	60				
	70				
Unidirectional (transverse)	50	√	√	√	√
	60				
	70				
Bi-directional	55	√	√		√
	58				
	61				

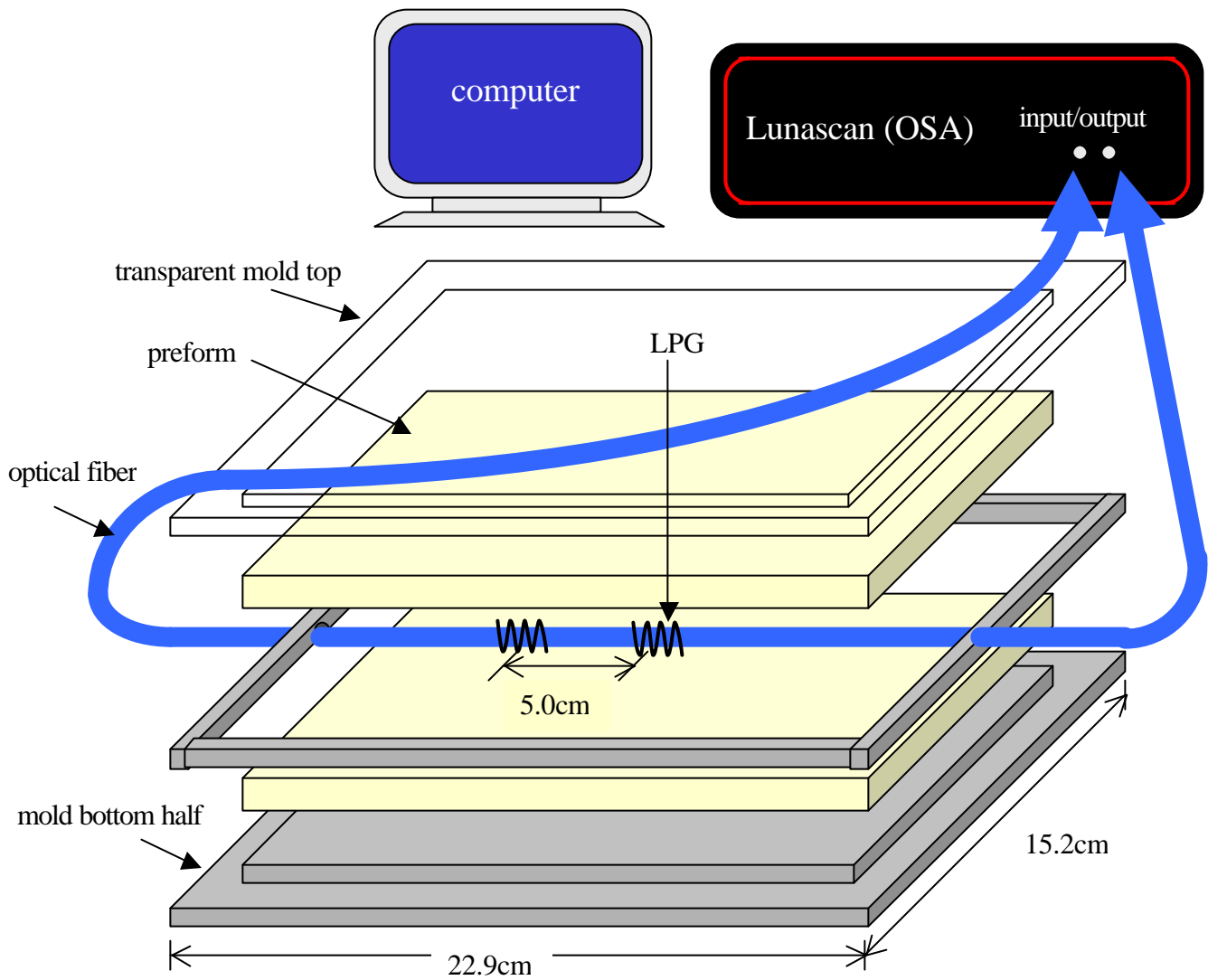


Figure 1: Schematic of mold and optical fiber assembly and experimental setup

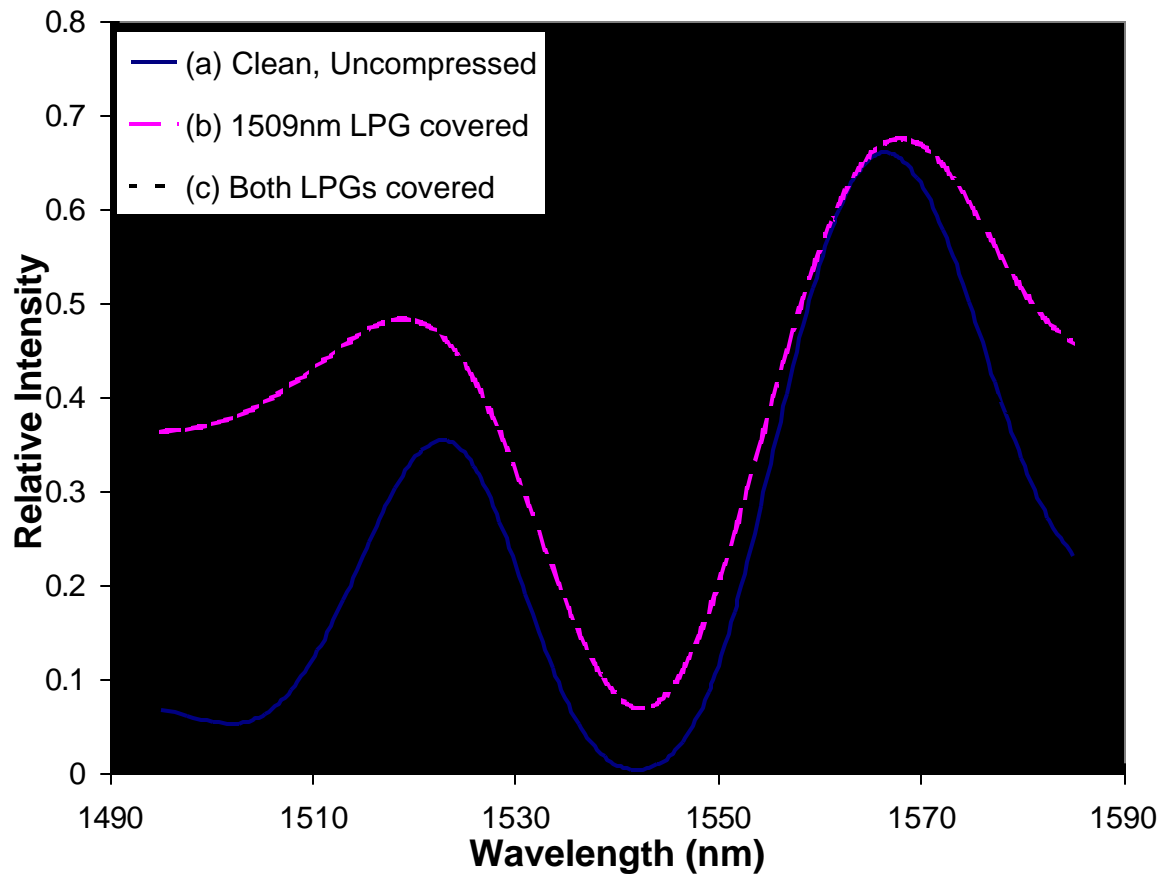


Figure 2: Spectrum of an optical fiber containing two LPGs written at 1509nm and 1549nm in (a) its clean, uncompressed state, (b) when the 1509nm LPG is covered by resin simulant and (c) when both LPGs are covered by the resin simulant



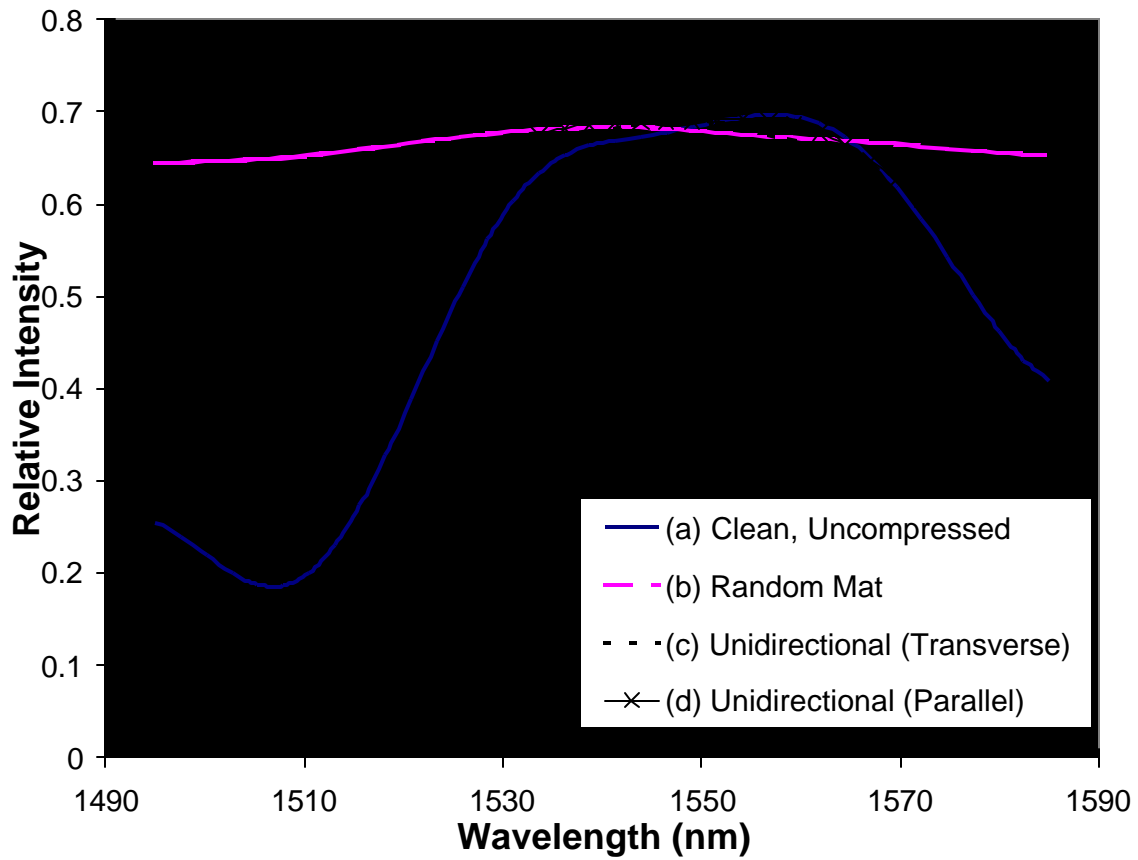


Figure 3: Spectrum of an optical fiber containing two LPGs written at 1509nm and 1549nm in (a) its clean, uncompressed state, when it is compressed in between (b) random mats ( $v_f=17\%$ ), (c) unidirectional mats with fiber transversely oriented with respect to the optical fiber ( $v_f=60\%$ ) and (d) unidirectional mats with fibers aligned parallel to the optical fiber ( $v_f=60\%$ )

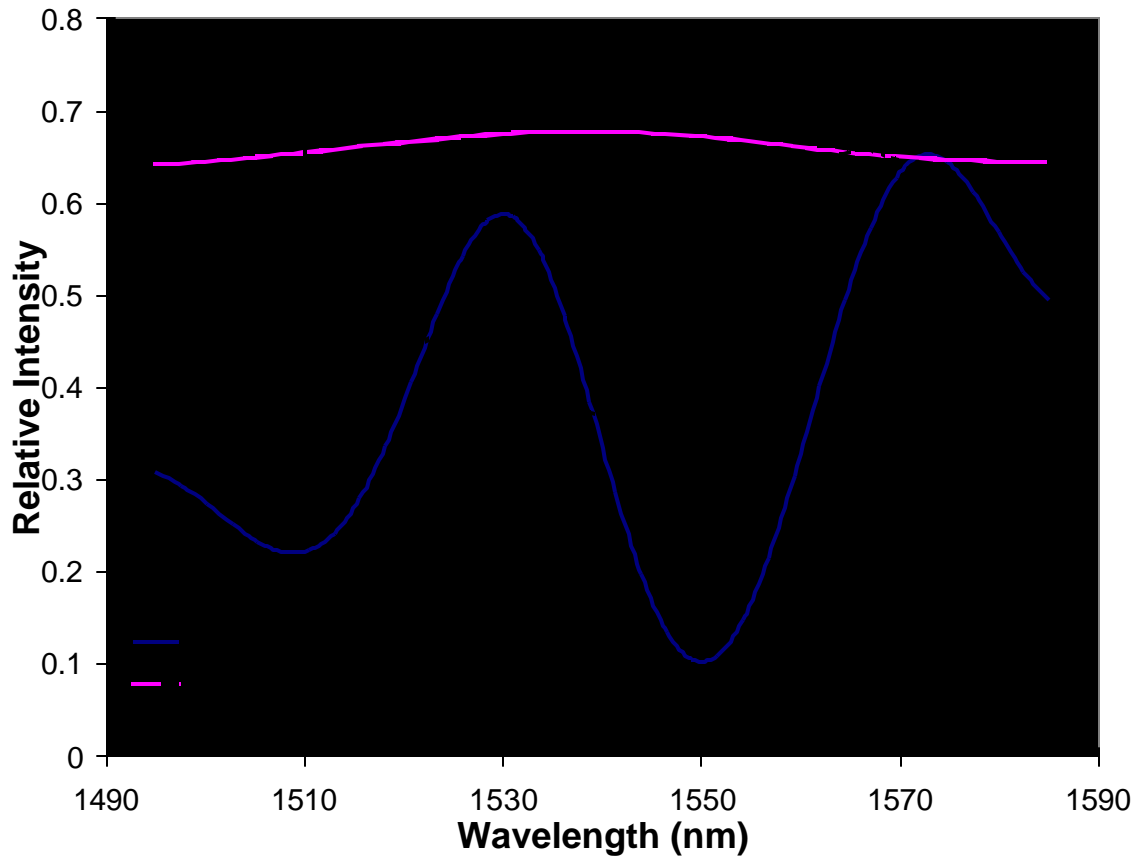


Figure 4: Spectrum of an optical fiber containing two LPGs written at 1508nm and 1549nm in (a) its clean, uncompressed state, when it is compressed in between (b) random mats ( $\nu_f=17\%$ ) without any protective sleeves and (c) random mats ( $\nu_f=17\%$ ) with the protective sleeves

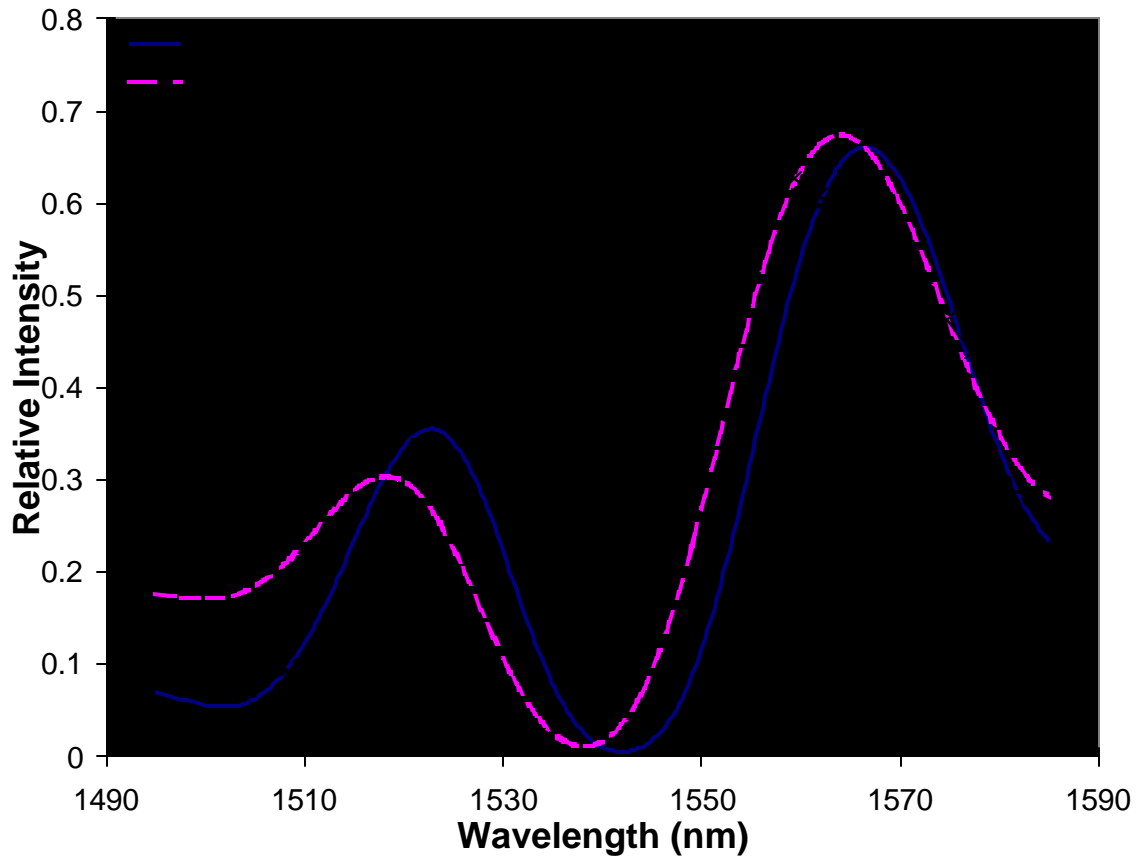


Figure 5: Spectrum of an optical fiber containing two LPGs written at 1508nm and 1549nm in (a) its clean, uncompressed state, (b) when it is compressed inside the mold with the hollow sleeves in place, when the resin simulant is injected into the mold and covers (c) the 1508nm LPG and (d) both LPGs