Monitoring of Advanced Composite Weave Structures Using Multi-Axis Fiber Grating Strain Sensors

Katy Davol, Eric Udd, Steve Kreger, Marley Kunzler, and Marty Laylor
Blue Road Research, Clear Creek Business Park
376 NE 219th Avenue, Gresham, Oregon 97030
503 667-7772, Fax: 503 667-7880, www.bluerr.com

Dirk Heider and Zhicheng Yu
University of Delaware, Center for Composite Materials
Newark, Delaware 19716
302 831-8898, Fax: 302 831-8525

Abstract

The feasibility of using multi-axis fiber grating strain sensors to monitor transverse strain and transverse strain gradients to complex, woven composite structures has been evaluated. This paper overviews the multi-axis fiber optic grating strain sensors and how they can be applied to measuring multidimensional strain fields interior to composite parts with complex composite weave structures. Experimental results are given for the case of a bi-axially woven composite coupon as well as for an E-glass/epoxy composite sample.

Multi Axis Fiber Grating Strain Sensors

In order to measure transverse strain and transverse strain gradients in textile composite materials multiaxis fiber grating strain sensors were used. A multi-axis fiber grating strain sensor is formed by writing a fiber grating onto birefringent polarization maintaining optical fiber. For this type of fiber grating strain sensor, a single fiber grating results in two distinct spectral peaks. These peaks correspond to each of the polarization axes of the polarization preserving fiber, which differ slightly in index of refraction. When the fiber is loaded transversely the relative index of refraction of the polarization axes of the fiber change and the net result is that the difference in wavelength between the spectral peaks changes as well. When the fiber is strained axially, the fiber elongates or compresses changing the fiber grating spectral period and the output spectrum goes to longer or shorter wavelengths respectively.

Figure 1a illustrates a multi axis grating written onto polarization preserving fiber, which is subject to uniform transverse loading. In this case the two spectral reflection peaks corresponding to the effective fiber gratings along each birefringent (polarization) axis will move apart or together uniformly providing a means to measure transverse strain[1,2,3,4]. In the case where load along the transverse axis is not uniform, as shown in Figure 1b, the peak associated with the nonuniform transverse load will split [1]. The transverse strain gradient can be measured quantitatively by the spectral separation between the peaks. The response of the fiber is approximately 1/3 of that of axial strain along the length of the fiber. As a specific example at 1300 nm a spectral shift of 0.01 nm along the fiber axis corresponds to 10 microstrain. A peak to peak separation of 0.01 nm due to nonuniform transverse strain corresponds to approximately 30 microstrain for 125 micron diameter bow tie polarization preserving fiber.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**
4. TITLE AND SUBTITLE **Monitoring of Advanced Composite Weave Structures Using Multi-Axis Fiber Grating Strain Sensors**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Blue Road Research,2555 NE 205th Avenue,Fairview,OR,97024**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

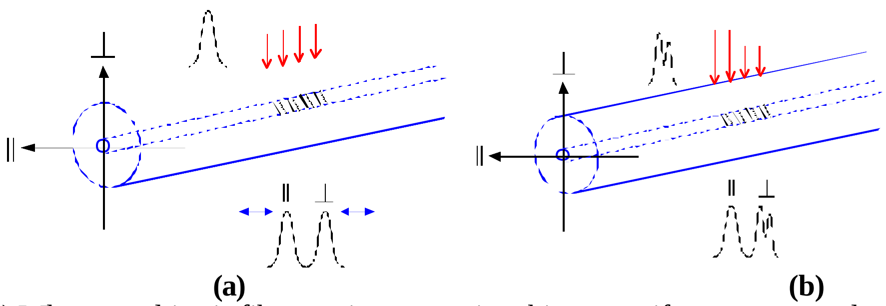


Figure 1. (a) When a multi-axis fiber grating sensor is subject to uniform transverse loading two spectral reflections result whose spectral separation is a measure of transverse strain. (b) When transverse strain across the fiber is not uniform along one of the birefringent (polarization) axes the peak associated with that axis splits, providing a means to measure transverse strain gradients effectively and quantitatively.

Textile Composite

A textile composite has internal structure on several scales. At the molecular scale, both the polymer matrix and the fibers exhibit structural details that profoundly affect strength and stiffness. On a coarser scale, typically ~1 mm, 103 – 104 fibers are bundled into yarns or tows. Within the finished composite, each as a highly anisotropic tow behaves as a solid entity. Because tows are rarely packed in straight, parallel arrays, stresses and strains often possess strong variations from tow to tow[5]. Many textile processes yield patterns of interlaced yarns or tows that repeat in one or two directions. They are periodic. The geometry of a periodic textile is conveniently described in terms of unit cells. The unit cell is defined as the repeated micro-structural unit. The entire textile can be constructed from spatially translated copies of this unit, without the use of rotations or reflections[5,6]. Figure 2 displays various perform architectures that can be used to support complex composite structures.

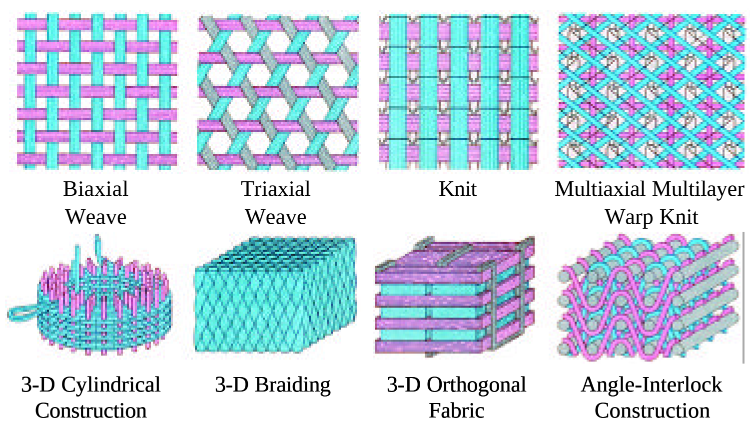


Figure 2. Preform architectures that can be used to support complex composite structures[7].

The complicated microstructure of textile composites results in local perturbation in the stress-strain relationship. Local strain varies as a function of location and is different from the global strain of the composite. The local deformation is also the source of cracking and failure initiation of textile composites. In order to measure local strain a sensor must be embedded into the perform. Multi axis fiber optical Bragg grating sensors are and ideal candidate for embedment because they are EMI resistant, their small size make them easily integrated into composite preforms at time of manufacture, and they have the ability to be multiplexed along a single optical fiber to obtain distributed complex strain field information.

Embedded Multi-axis Fiber Grating Strain Sensors Used to Measure Multi-axial Strain in a Biaxial Woven Composite Structure

By using the complex weave structures shown in Figure 2 it is possible to greatly increase the overall mechanical properties of the composite structure. As an example, a biaxial weave structure was used to support the fabrication of a small composite coupon for testing. Multi-axis fiber gratings were placed in the four-layer coupon between the first and second layers and between the second and third layers as show in Figure 3.

The multi-axis fiber grating strain sensors with an overall length of approximately 5 mm were aligned orthogonal to the weave structure, which has a period of approximately 2 mm. The result is that the axis of multi-axis fiber grating strain sensor that is orthogonal to the plane of the coupon has two primary components of transverse strain due to the biaxial weave structure, while the axis that is parallel to the plan of the coupon has one principal component of transverse strain due to the resin associated with the composite part of Figure 3.

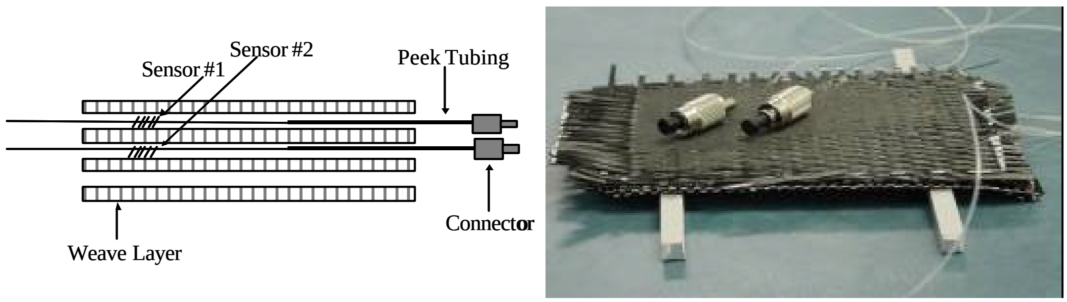
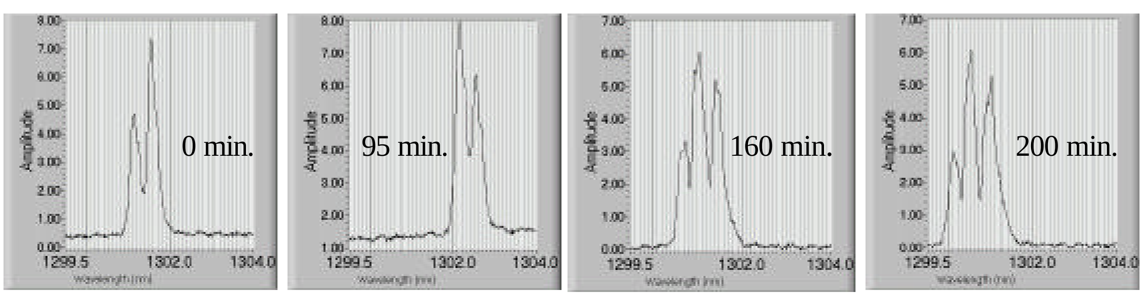


Figure 3. Multi-axis fiber grating strain sensors were placed between the first and second and second and third layers of a biaxial composite weave.

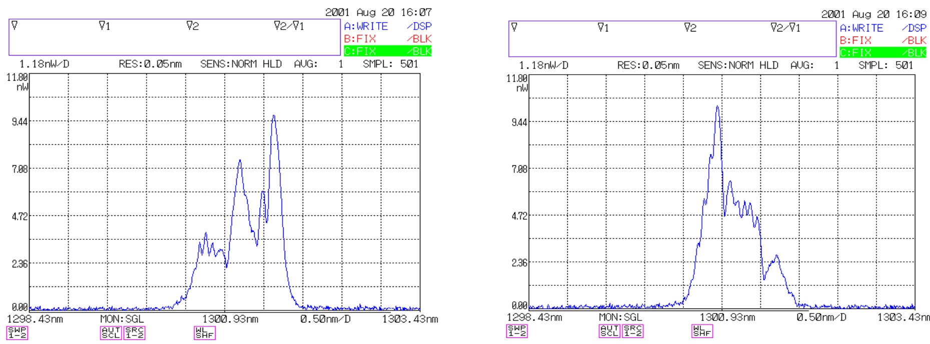
When the part is curing the two spectral peaks associated with the multi-axis fiber grating sensor move toward longer wavelengths as the cure temperature rises, allowing the internal temperature of the composite part to be measured. The part shown in Figure 3 was constructed using prepreg tow material manufactured by Thiokol and has a cure temperature of 190 degrees C. When the part reaches this temperature the resin structure starts to cross link resulting in transverse and axial compression on the multi-axis fiber grating strain sensor, shown in Figure 4c. The overall spectral structure moves toward shorter wavelengths indicating compression in axial strain.



(a) **(b)** **(c)** **(d)**

Figure 4. Sensor 2 was monitored during the cure cycle. (a), (b) Increasing temperature to peak temperature; (c), (d) cool down.

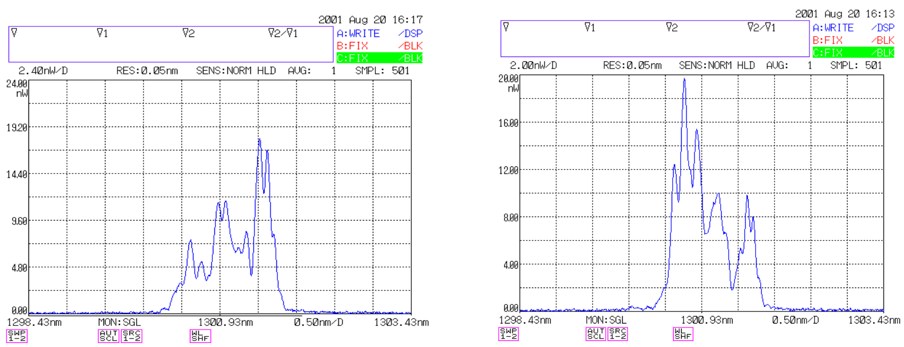
Each of the principal orthogonal axes of the birefringent fiber can be interrogated individually by using a fiber polarizer placed in front of the light source in combination with a Lyot depolarizer. Figure 5a shows the spectral peaks from the multi-axis fiber grating strain sensor in the upper portion of the composite part for the case orthogonal to the part. The two principal peaks corresponding to the biaxial weave are spaced spectrally by 0.50 nm, which corresponds to a transverse strain difference of 1500 micro-strain. The amplitude of the spectral peaks indicates the relative length of the fiber grating subject to the specific transverse force. In the case of Figure 5a the principal peak is about 20 percent larger indicating that the length of the fiber grating subject to this loading is 20 percent longer than that of the next largest peak. There is a third set of much smaller peaks again centered about 0.50 nm from the second peak and 1.0 nm from the first. These peaks correspond to transverse strain gradients over much shorter lengths of the fiber grating; their transverse strain levels are 1500 to 3000 micro-strain lower than the second and first principal peaks respectively. Figure 5b shows the axis that is aligned in the plane of the part. In this case the weave structure does not come in direct contact with this axis and there is one principal peak. Transverse strain gradients along this axis appear along relatively small lengths of the fiber grating.



(a) **(b)**

Figure 5. (a) Spectral response of the multi-axis fiber grating strain sensor along the axis orthogonal to the plane of the part is used to quantitatively measure multi-axis strain fields. (b) Spectral response of the multi-axis fiber grating strain sensor along the axis in the plane of the part to quantitatively measure multi-axis strain fields.

Measurements were also made on the multi-axis fiber grating strain Sensor 2, which was positioned between the second and third layer of the test part shown in Figure 3.



(a) **(b)**

Figure 6. (a) Spectral response of the multi-axis fiber grating strain sensor 2 along the axis orthogonal to the plane of the part is used to quantitatively measure multi-axis strain fields. (b) Spectral response of the multi-axis fiber grating strain sensor 2 along the axis in the plane of the part to quantitatively measure multi-axis strain fields.

In Figure 6 the spectral response of multi-axis fiber grating strain Sensor 2 is shown. As with Sensor 1 there are two distinct principal peaks associated with the transverse sensing axis that is orthogonal to the plane of the test part. Since Sensor 2 is "deeper" into the part it would be expected that transverse loading would be more complex and this shows up as transverse strain gradient details across the principal peaks in Figure 6a. A similar result occurs for the principal peak in the plane of the part shown in Figure 6b. These results are expected because of the interactions between multiple layers of biaxial weave above and below Sensor 2.

Embedded Multi-axis Fiber Grating Strain Sensors Used to Measure Multi-axial Strain in a E-glass/epoxy Composite Sample

A composite panel was made by the Vacuum-Assisted Resin Transfer Molding process (VARTM). The preform was molded by stacking several fabric layers. The fabric that contained the embedded optical fiber sensor was put as the second layer on the top of the preform stack. The resin system, SC-15 epoxy from API, was used during infusion.

The response of the sensor in different stages of the VARTM process was recorded. Figure 7 shows the reflection results of a dual axis sensor before vacuum was applied, during vacuum application, following the complete resin infusion, and after the complete cure. The epoxy resin system was cured at room temperature, without measurable exothermal reaction.

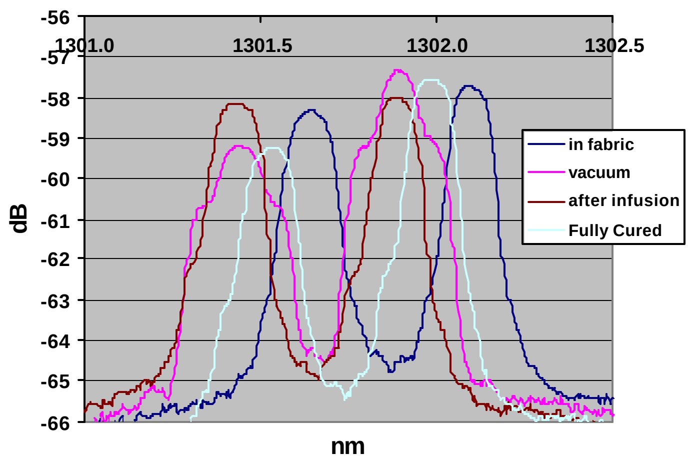


Figure 7. Response of dual axis grating sensor during VARTM processing.

The wavelength response under vacuum for the dual axis grating shows that the sensor is under compression. A broadening of the wavelength distribution can be seen as well. This effect disappears during infusion, when the resin lubricates the fabric-sensor interface and the sensor slips into a more uniform stress state.

Compressive and tensile loads are also applied to the dual grating test specimens. The samples were cut from the textile composite panel with a dual grating sensor in the middle of its width. The size of the sample is approximately 3 inch in width and 0.27inch in depth.

The specimens were loaded by three point bending. The grating portion of the dual axis grating sensor was put beneath the load head. Compressive and tensile strain conditions could be applied by turning over the panel. Using the polarization setup, only one peak of dual axis sensor was measured.

With an increased compressive load, the wavelength peaks moved toward the shorter wavelengths. The sensor shows an increase in strain variation as a function of load. This change is well behaved until approximately 400 loading. Further loading resulted in fiber breakage and a dramatic change in the wavelength distribution. At the highest load, individual composite fibers started to break and the strain along the fiber varies dramatically resulting in a very broad wavelength response.

Using the method described above, a dual axis grating optical fiber sensor interior to an E-glass/epoxy composite test specimen was loaded using the three point bending test fixture. The results are illustrated in Figure 8 and Figure 9. Peak splitting occurred when the load reached a level around 104lb and a bending displacement of 0.11inches. According to the data gathered, it can be estimated that the strain gradient corresponding to the peak splitting of the dual axis grating is about 27.4 micro-strain per millimeter in E-glass/epoxy composites.

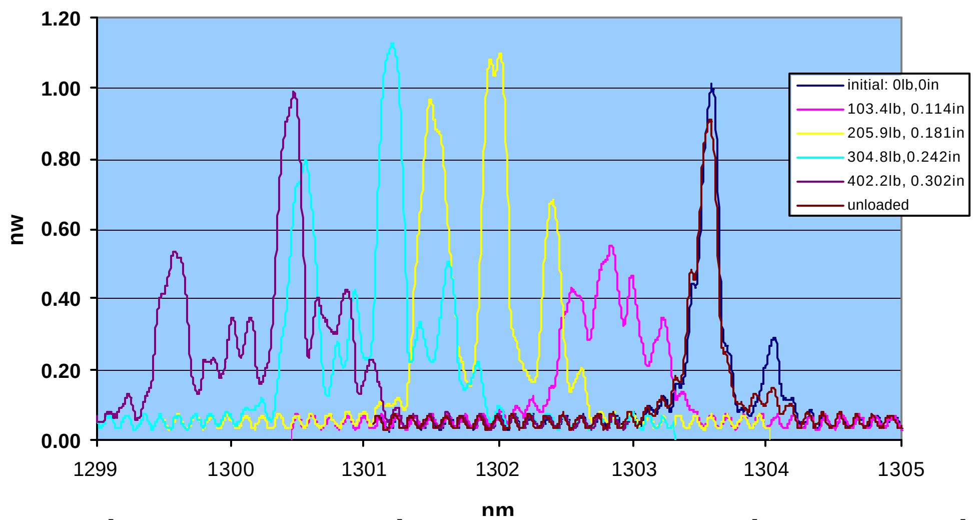


Figure 8. Dual axis grating sensor in glass/epoxy composites strained in compression, left peak

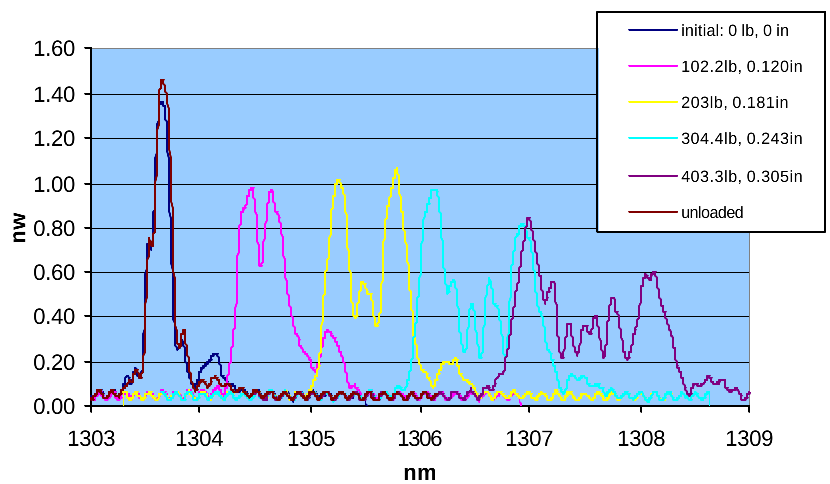


Figure 9. Dual axis grating sensor in E-glass/epoxy composites strained in Tension, left peak

Summary

Multi-axis fiber Bragg grating sensors have the capability of measuring multi-components simultaneously and are very suitable to be embedded in composite materials for multiplexed measurements. The advantage of these sensors is their capability to measure strain gradients over the length of the sensor, thus providing an accurate description of the strain distribution on the composite unit cell.

The multi-axis strain sensing capabilities have useful applications in health monitoring for crack detection and damage assessment beyond the capabilities of single axis fiber grating strain sensors[8].

Acknowledgement

This work was partially supported under an SBIR STTR Phase I grant from the Air Force Office of Scientific Research under contract number F49620-01-C-0007. Blue Road Research and the University of Delaware would like to gratefully acknowledge this support.

References

1. Perez, H.L. Cui, E. Udd, "Acoustic Emission Detection using Fiber Bragg Gratings", Proceedings of SPIE, Vol 4328, p. 209, 2001.

2. E. Udd, W.L. Schulz, J.M. Seim, E. Haugse, A. Trego, P.E. Johnson, T.E. Bennett, D.V. Nelson, A. Makino, "Multidimensional Strain Field Measurements using Fiber Optic Grating Sensors", Proceedings of SPIE, Vol. 3986, p. 254, 2000.

3. W.L. Schulz, E. Udd, J.M. Seim, A. Trego, I.M. Perez, "Progress on Monitoring of Adhesive Joints using Multiaxis Fiber Grating Sensors", Proceedings of SPIE, Vol. 3991, p. 52, 2000.

4. E. Udd, W.L. Schulz, J.M. Seim, E. Haugse, A. Trego, P.E. Johnson, T.E. Bennett, D.V. Nelson, A. Makino, "Multidimensional Strain Field Measurements using Fiber Optic Grating Sensors", Proceedings of SPIE, Vol. 3986, p. 254, 2000.

5. Brian N. Cox, Handbook of Analytical Methods for Textile Composites. NASA Contractor Report 4750(1997)

6. T-W, Chou, Microstructural Design of Fiber Composites. Cambridge Press, UK(1992).

7. Chou, T-W., R. L. McCullough and R. B. Pipes, 1986. "Composites," *Scientific American*, 254, 193.

8. Y. Okabe, T. Mizutani, S. Yahiro and N. Takeda, "Application of Small Diameter FBG Sensors for Detection of Damage in Composites", SPIE Proceedings, Vol. 4328, p. 295, 2001.