

Integrated Optical Transceiver for Inertial Sensors Using Polymer Waveguide Technology

Mark Temmen*, William Diffey, and Paul Ashley
U.S. Army RDECOM

Aviation and Missile Research, Development, and Engineering Center
Redstone Arsenal, Alabama 35898

ABSTRACT

The application of polymer technology in integrated optical components provides a method of increasing the level of integration with the real potential of reducing unit cost. This paper describes the application of this technology in an integrated optical transceiver unit designed for an inertial sensor system, or more specifically, for an interferometric fiber optic gyroscope (IFOG) system. The design and fabrication of the optical polymer waveguide component and its integration with other discrete components to construct a transceiver is described.

1. INTRODUCTION

Advances in interferometric fiber optic gyroscope (IFOG) technology have largely come to rely upon lithium niobate modulators for the phase modulation required for rotation measurement. While this type of modulator performs very well, it is of a discrete component nature when considering integration with other system components. Also, the production of lithium niobate and its processing to produce a modulator does not promote a low cost potential for manufacture. Alternatively, nonlinear optical polymer materials have been developed and formed into suitable modulators for IFOG implementation (Ashley and Cites, 1997). These polymer devices can be manufactured with semiconductor wafer level type microfabrication processes, which can potentially reduce single device costs. Integrated optic systems components built around these polymer modulators and fiber coils can also be tightly integrated to reduce overall package volume. Here we describe the design, fabrication, and integration of a polymer integrated optic transceiver for applications in IFOG systems.

For optical gyroscopes, the Sagnac effect is the physical phenomenon that enables the measurement of rotation. In an IFOG configuration, counter propagating

optical beams in a fiber waveguide coil experience a net propagation path difference when the coil experiences a rotation in the axis of the coil. These path differences produce a phase shift in their interference pattern that is measured at a detection plane. The phase shift, $\Delta\Phi$, can be expressed as

$$\Delta\Phi = \frac{2\pi LD}{lc} \Omega \quad (1)$$

where Ω is the rotation rate, L , the length of the optical paths, D , and the diameter of the paths or fiber coils, l is the wavelength of operation, and c is the propagation velocity in the fiber coils.

Figure 1 shows a schematic for an optical implementation for detection of the phase shift using integrated optic components. A superluminescent diode (SLD) source or a fiber source (typically a laser pumped Erbium doped fiber) produces short coherence length light that is fed into one port of a 4 port coupler. Of the two outputs of the coupler, one may be unused or it may be used to monitor source power. The other output provides the light to a Y branch waveguide. Upon the exit from the Y branch, each beam passes through a phase modulator that are necessary to create a nonreciprocal phase modulation in the system for an unambiguous direction measurement of the rotation. After the modulators, the two beams counter propagate through a fiber optic coil which can have many turns for longer length L , which increases the magnitude of the net phase shift. (eq. 1). The optical beams are then fed back through the Y branch and coupler and interfered on a detector. The amplitude modulation of their interference pattern is proportional to the rotation rate of the system. To maintain good output signal to noise level, a preamplifier is usually used to amplify the output. System feedback electronics can drive phase modulators for closed loop operation to stabilize the interferometric amplitude or fringe pattern. Depolarizers may be used to mitigate signal fading from polarization losses in the fiber coil.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 00 DEC 2004		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Integrated Optical Transceiver for Inertial Sensors Using Polymer Waveguide Technology				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) U.S. Army RDECOM Aviation and Missile Research, Development, and Engineering Center Redstone Arsenal, Alabama 35898				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 See also ADM001736, Proceedings for the Army Science Conference (24th) Held on 29 November - 2 December 2005 in Orlando, Florida. , The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

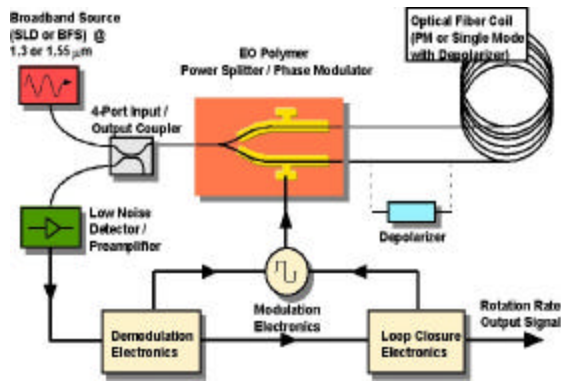


Figure 1 - Optical implementation to detect phase shift

2. CONCEPT AND DESIGN

Microfabrication technology using polymers allows the construction of the optical circuit components, i.e. the waveguides, coupler, Y branch or power splitter, and phase modulators to be implemented on a single substrate. The substrate for this optical circuit uses the silicon wafer as a silicon optical bench or platform for all these circuit components. Figure 2 shows the implementation concept using a SLD as the source with the detector and pre-amp and polymer optical circuit waveguide components onto a silicon substrate. Phase modulators are also implemented on this polymer substrate with the inclusion of a designed electrode pattern to generate the electric field across the non-linear optical polymer. The outputs are pigtailed providing the connections to the fiber coil loop.

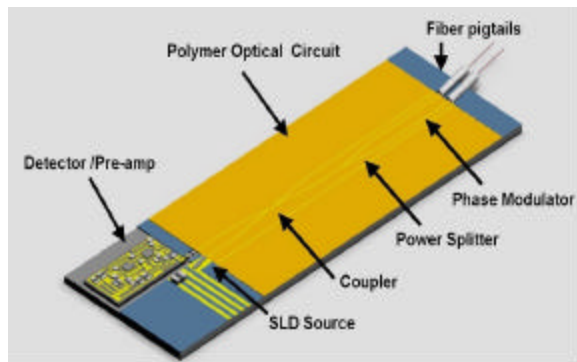


Figure 2 – SLD source, detector with preamplifier, coupler, Y junction, and phase modulators integrated for the basis of a single axis optical circuit for an IFOG. Fiber coils are attached at the end to complete the circuit.

Development of the first components of this silicon optical bench, specifically, the source, detector, preamplifier, waveguide, and coupler into a stand-alone transceiver unit was undertaken. This integrated transceiver unit could then provide the needed baseline functionality for further development with a wide variety

of modulator technology areas with either organic or inorganic materials. Development of a single integrated transceiver/modulator could be accomplished then with a mature modulator material. A schematic of the transceiver functionality is shown in Figure 3. Included in this concept is a thermoelectric cooler for power and wavelength stabilization of the source.

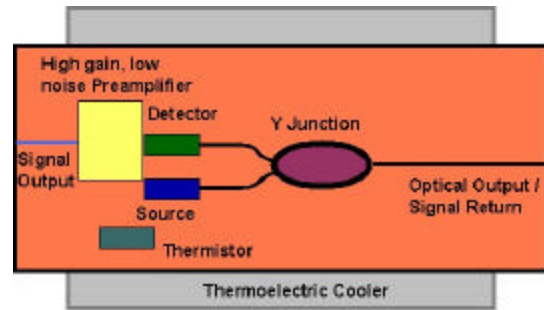


Figure 3 - Transceiver Functionality Schematic

After sizing the prospective discrete components, a layout and design was generated for the transceiver. A transceiver chip design required an area to mount the preamplifier, a coupler or Y branch optical waveguide, and other components such as a SLD source, detector element, thermistor, wire bonding pads and electrical circuit traces and grounding planes. This optical circuit chip or silicon optical bench transceiver is then mounted into a metal housing package. Housed underneath the optical circuit chip in the housing is a thermoelectric cooler. The requirements for the pinout pattern for this package is a standard 14 pin dual in line pattern for the telecom industry.

Several complex integration issues for the transceiver must be considered in the design. Integration issues include optical crosstalk, optical isolation, mechanical stability, thermal management, and electrical crosstalk (Ashley et al., 2002, 2001). Optical crosstalk describes the unwanted background light present on the detector. This is often suppressed with absorption materials and proper placement of components to minimize the direct path for scattering. Optical isolation techniques prevent the chip optical facets from reflecting light back at favorable angles for coupling back into waveguides. This light then manifests itself as background noise and reduces the system rotation signal dynamic range. Angle cuts and angle polishes for these coupling interfaces significantly reduce this reflected light. Mechanical stability in the placement of the components is required to maintain stable coupling of the light from one component into another. A proper choice of substrate materials and thicknesses provides the best means for maintaining stability. Thermal management is key to preventing the source from drifting in wavelength and power. Wavelength drift manifests itself as phase noise and

consequently intensity fluctuations at the detector plane. These fluctuations can be erroneously interpreted in system data as phase shifts due to rotation. Electrical crosstalk can be generated from outside sources and from modulator electronics that can interfere with signal integrity resulting in reduced system sensitivity.

3. COMPONENTS

3.1 Waveguide design

The polymer waveguide design for the transceiver uses polyimides to obtain the necessary refractive index profiles for optical confinement. The outline of the waveguide design is shown in figure 4. A rib structure is etched and covered with an upper cladding of Norland optical adhesive.

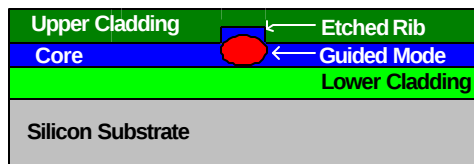


Figure 4. Polymer waveguide design for 1550 nm.

3.2 Source

SLDs were chosen for the system source due to the increasing powers available and small size compared to a fiber source. Figure 5 shows a possible SLD layout that could be used during this development. All versions of SLD fabricated today utilize the angle stripe design for optical isolation. All devices are capable of several tens of milliwatts of light output. Designs for either 1310nm or 1550 nm are available. Different vendors utilize different design absorbers also.

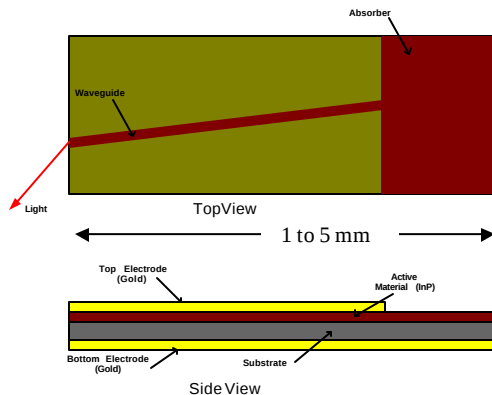


Figure 5– Possible layout for a SLD source.

Other important considerations for the sources are the coherence spectrum and the power and wavelength stability. Figure 6 shows the coherence spectrum of an SLD. System signal coherence paths are adjusted to lie in flat area of this spectrum. A low noise spectrum allows for more dynamic range of signal and therefore more gyroscope sensitivity.

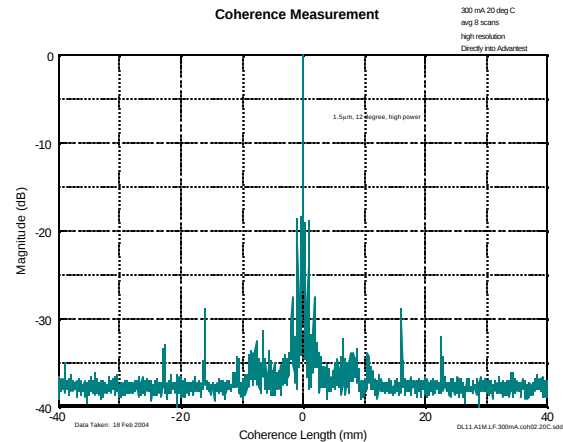


Figure 6 - SLD coherence spectrum

The optical power output stability of a transceiver is shown in figure 7. Temperature stability is necessary for constant power output. With the operational point at 20 degree C, the power is seen to drop to less than .7 of this power at 30 deg C. Environmental effects can markedly influence this stability hence the need for a thermoelectric cooler/heater in the transceiver package.

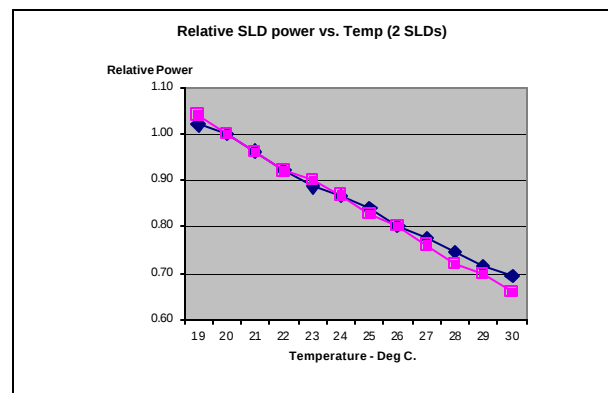


Figure 7 - SLD power output vs. temperature

4. FABRICATION

Program goals for the fabrication strive for using standard microfabrication processes and equipment. Fabrication of the couplers and the modulators is initiated with a silicon nitride coated wafer. This provides the electrical isolation for modulator connections. Sputter metal deposition, spin coating application of polymer

materials, and positive resist technology are used for the application and patterning of material for the traces, electrodes, waveguides, and contacts.

Waveguide backscatter promotes propagation losses and was improved with the use of masks written on laser writers. Contact mask aligners were initially used for waveguide patterning but projection aligner lithography is now used with improved results due to waveguide sidewall roughness.

To complete the patterning processes, the etching techniques used were performed in reactive ion etchers. Both the charge coupled and inductively coupled plasma processes using primarily oxygen were used for the polymer etching. Figure 8 shows a completed transceiver wafer (100mm diameter) with 6 devices before dicing. All the process steps are completed on this wafer.

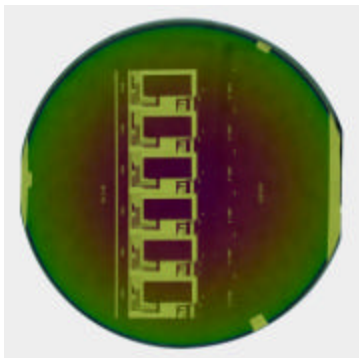


Figure 8 - Wafer layout of six transceivers

Although standard microfabrication techniques are used in the majority of process steps in fabricating a wafer of transceiver devices several new microfabrication processes for the transceiver were developed. Specialty processes were developed to produce smooth vertical polymer facets process for the efficient coupling of light, and processes for the formation of features for the rapid placement of components such as the detector were also developed.

Fabrication processes waveguide facet formation use deep (inductively coupled) reactive ion etching (DRIE). DRIE machines were also used to etch other polymer and silicon reliefs in the substrate for the mounting of the detector. Each of these fabrication steps had a unique etch process involving etch chemistries and schedule, along with different masking steps and materials tailored to work with this polymer/silicon waveguide substrate. Figure 9 shows the polymer facet for SLD to waveguide coupling. The process (Diffey, Temmen, Ashley, 2004) yielded a smooth facet in the core layer that helped reduce backscattering of light.

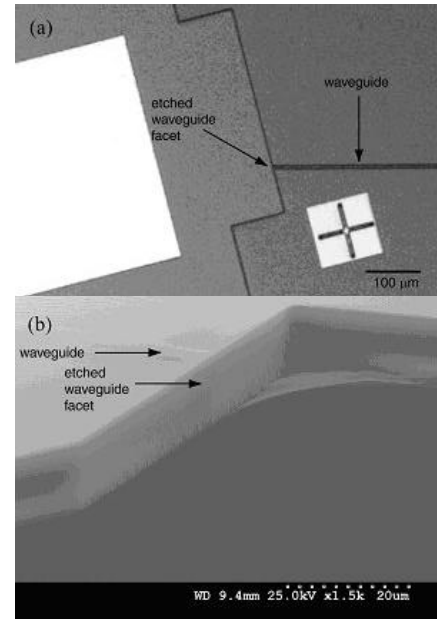


Figure 9 - Polymer facet fabrication a) location of facet on the transceiver, b) waveguide facet quality in the polymer

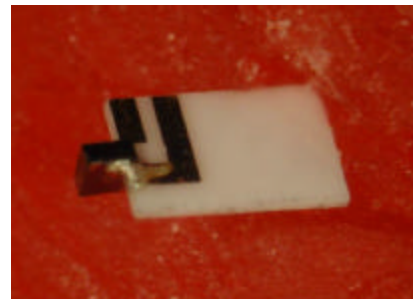
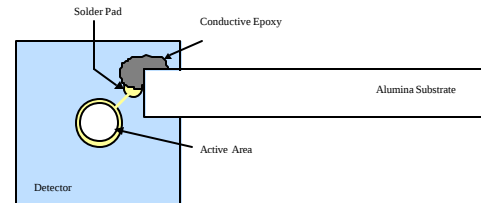


Figure 10 - Waveguide facet and detector polymer well

Figure 10 show the silicon etch step necessary to produce a relief in the silicon optical bench to place the detector. After patterning and etching the polymer, DRIE is used again with different parameters to etch into the silicon. The isotropic etch undercuts the polymer areas but this does not affect performance. The waveguide from the bottom of the figure is the path for the return optical signal. The detector is placed and registered in the silicon-polymer relief with sufficient accuracy and epoxied into place.

5. INTEGRATION

To demonstrate the ability to produce the transceiver in a more automated fashion for manufacturing, an automated pick and placement machine was acquired. The pick and place machine was setup for the placement of the source SLD onto the waveguide substrate or the silicon optical bench. The pick and place machine is shown in Figure 11. It consists of an X-Y moveable stages mounted onto a granite base. Mounted on a granite yoke above the stages is a fixture capable of vertical and rotational movement. This upper fixture holds the items to be placed, in this case the source SLD die, and lowers it onto the substrate.



Figure 11 - Pick and Place Machine

This upper fixture is outfitted with different tools and chucks for the different die it is to handle and place. Embedded in this upper fixture is a heater for curing epoxy or melting solder. The bottom stages also have heaters incorporated in them for the same purpose. Cameras are used in conjunction with the computer control to pick up components from storage packs and use the image data to perform the coarse automatic alignment for placement. Control of stage movement manually for fine alignment allows precise placement of the SLD.

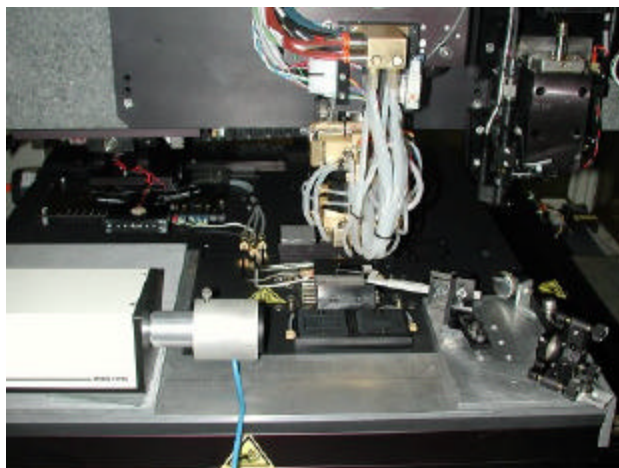


Figure 12 - Optical Feedback for source alignment

For the final alignment of the SLD an optical feedback system was setup. An electrical potential is placed on the upper fixture and SLD and upon lowering it onto the substrate it contacts uncured conductive epoxy. This completes the electrical circuit for activating the SLD. Output from the location of the waveguide exit on the substrate chip is imaged and monitored with a radiometer for maximum output and best alignment. Figure 12 shows this setup for optical feedback. The light exits the SLD/substrate to the right and is directed to the radiometer for measurement.

After the SLD is aligned and cured onto the substrate chip or silicon optical bench, other components are then placed onto the chip. A thermistor, preamplifier, and detector are manually placed and attached with epoxies. Additional heatsinking is also placed on top of the source SLD to assist in thermal energy transfer to the substrate.

A housing is machined from either brass or Kovar into which pins are mounted. A thermoelectric cooler is placed in the housing as shown in figure 13. The thermoelectric cooler supports the entire substrate or silicon optical bench. Placement of the silicon optical bench onto the cooler is accomplished manually with no critical alignment as shown in figure 14. Once the epoxies are cured, the connections between the pins and the traces are wirebonded.

Figure 15 and 16 shows the transceiver assembly for an integrated optical circuit for implementation in an IFOG system. Two rows of 7 pins each provide for all other power and signal inputs. The output fiber is a 80 micron diameter PM fiber and is supported by a teflon jacket.

This transceiver section was separated and developed as a stand alone unit to be used as a source for various other system components. Modulators, fiber coils, and

other silicon optical bench type integrated optical circuit components can be tested using the transceiver as a source. The source can be modulated or run cw. Table 1 lists some performance values.



Figure 13- Housing showing the thermoelectric cooler in place



Figure 14 - Transceiver package

Table 1 – Transceiver Specifications

Wavelength	1300, 1550 nm
Output power:	1.25 mW Polarized (300ma, 20deg C)
Bandwidth	8-10 MHz
Gain	.5 – 1×10^6
Power reqmts	+/-5V, +15V

While the preliminary transceiver performed very well, other specific application requirements stipulated the necessity of a reduced package size. Therefore, a new wafer level mask set for a much smaller waveguide chip or silicon optical bench was generated. The results of this size reduction are shown in Figure 9. This transceiver, while being smaller, has the same functionality and performance as the preliminary design. Also, using this size silicon optical chip, a standard 100 mm diameter wafer used in fabrication can potentially accommodate at least 24 chips. The package dimensions are 28 mm length, 7mm height, and 12.5 mm width. The pin pitch and row spacing are made to accommodate a 14 pin DIP socket common for telecom type packaging. It has a thermoelectric cooler incorporated internally. The housing is fabricated from brass with electroplated layer of gold deposited on it for electrical shielding. The output is through a PM fiber as in the preliminary device. Final

integration of this transceiver with an optical modulator and is in development.



Figure 17 – Packaged transceiver module.



Figure 18 – Packaged transceiver module.

CONCLUSIONS

A transceiver has been developed using polymer waveguide technologies with the goal of maintaining wafer level production of components. The manufacture of transceivers using technologies such as pick and place machines has been shown. The versatility of the developed transceiver does not allow its application be limited to IFOG systems but to other types of fiber sensing systems also.

REFERENCES

P.R. Ashley and J.S. Cites, "EO polymer devices for fiber-optics gyros and other applications," *OSA Technical Digest Series*, 14, 196 (1997).

P.R. Ashley, M. Temmen, and M. Sanghadasa, "Applications of SLDs in Fiber Optic Gyroscopes," Proc. of SPIE Photonics West Conf., San Jose, CA, Vol. 4648, (19-25 Jan. 2002).

P.R. Ashley, G.A. Lindsay, M. D. Bramson, "Polymer Waveguide Devices for Inertial Sensors", OWA2, Proc. of OSA Annual Meeting, Long Beach, CA (14-18 Oct. 2001).

W. M. Diffey, M.G. Temmen, P. R. Ashley, "Fabrication of Low Loss, Optical Quality Polymer Waveguide Facets in Multilayer Polymer Devices Using an Inductively Coupled Plasma", Proceedings of the Eleventh Meeting of the Symposium on Polymers for Microelectronics at Winterthur, Wilmington, Delaware, (May 2004)