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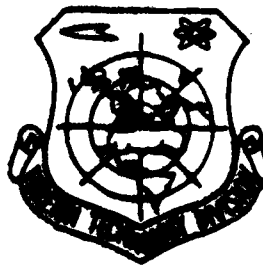
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## THE PRESENT SITUATION AND APPLICATION OF INTEGRATED OPTICS

by Du Haiping

(1)

Integrated optics is a new field for the study of theories related to optical paths and its core problem is integrated optical paths. So-called integrated optical paths are similar to integrated circuits, that is they are a combination of each of its parts such as the light source, light wave guide, coupler, modulator, light switch, light filter and probe and use a film form to integrate and complete a new function.

Obviously, the special characteristics of the integrated optical path is its "integration" and its "optical path".

"Integration" points to the pattern of the structure and originates from the integrated circuit. In the 1960's, the development of the miraculous integrated circuit not only had a tremendous influence on electronic computers and all electronic technology but it also gave inspiration to many other forms of

technology to use integrated patterns to attain the outstanding functions of miniaturation and high dependability. Integration technology has developed quickly and now we not only have integrated circuits but also magnetic path integration (CCD) and optical path integration.

The use of the integrated pattern demands that the structure of each component have a film form. Many cases have proven that optical components with the film form are not only needed for the integrated pattern but also at present many components have improved the effective functioning of the optical components. For example, the function of the patterned control and selection of the film semiconductor laser is superior to common semiconductor lasers.

Much technology has been gained on the film type optical components and based on the dissimilarities of materials we can differentiate the uses of evaporation, illumination, extension, splattering, photoetching, corrosion, polymerization and mould pressing. Because the operating frequency band of the integrated optical path is high (operating wavelength is about 1 micron), the demand for component measurement precision is very stringent and because of this, technical difficulties are great. For example, for the light wave guide to decrease scattering loss when the light

is transmitted, the surface light cleanliness cannot be lower than 0.05 microns. To reach this high precision, the technical difficulty can be conceived and known. No wonder some people say that the technical difficulty and precision of integrated optical paths are not inferior to large-scale integrated circuits and in some respects are even greater.

So-called "optical paths", as the name implies, are light beams when transmitted and they are composed of various optical components with dissimilar functions. Compared to electric circuits, optical paths are not only different in composition but even more so have a very large difference in operational frequency. In electric circuits, there is a source component with a greater oscillating frequency of several ten to several hundred megahertz which belongs to the microwave wave band. In optical paths, the oscillating frequency of the laser is high and reaches a light frequency band 4 to 5 numbers higher than the microwave wave band.

We know that in electronic technology there is continuous development and this opens up new frequency bands that advance towards high frequency. Generally speaking, because frequency is higher, the received and handled information is greater and the function of the electronic equipment is superior. Before the appearance of the laser, the highest oscillation frequency emitted



by the active electronic parts (such as the electron tube, crystal tube, diode etc.) was several hundred thousand mageshertz, the wavelength was in millimeters and in the submillimeter quantum level, the distance of the wavelength was in microns. The light frequency band in the submillimeter quantum level also had a corresponding distance. After the appearance of the laser, people attained an ideal sine wave oscillation source in the light frequency band. From this, a whole set of things in radio electronics technology gradually expanded in the light frequency band and gradually brought about the use of a new form in light frequency bands.

Therefore, from the view of the light frequency electronics angle, integrated optical paths are a type of high level advanced stage of integrated circuits. With the development of integrated circuits, in space, integration size has become larger and larger and there has been large-scale integration and super large-scale integration. In time, the operational frequency has gotten higher and higher and there are not only microwave integration circuits but now we also have the handling of light wave integration circuits which are integration optical paths. (Naturally, integrated optical paths are not based on the suggestion of this one idea).

Technological progress commonly follows in order, advances

step by step and accumulates bit by bit. Integrated optical paths have raised the frequency quantity level to several times that of the integrated circuit. This is indeed a tremendous leap. In the face of this type of leap, the great majority of present technology has not kept abreast of it and still needs to be sought, developed transformed and raised. Looking at it in this way, integrated optical paths can be reckoned as a "premature child". When people mentioned the concept of the integrated path in 1969, everyone was still vague about it. At that time, not only had they still not presented a substance but even the materials used to create the questions based on these theories were not entirely clear. Through the investigations and research done in the last ten years, integrated optics were bred and developed. Today it is in the process of being transformed from pure concept to reality.

(2)

In the last ten years, integrated optics have developed quickly and research work has been very successful. A rough estimate is that during this period, there have been internationally over one thousand articles published in major newspapers, magazines and academic conferences. There have also been 7 to 8 large scale international conferences held in the United States, Japan and Western Europe. The technological development over the last ten

years can be summed up in the following four main points:

1. The laying of a theoretical foundation. The essential theoretical problem of integrated optical paths is the medium wave guide theory which helps people to understand the physical quality of optical phenomenon in wave guide and it is used to direct optical return circuits and the planning and development work for each component.

The medium wave guide theory is an electromagnetic wave theory based on Maxwell's equation and the geometrical optics method has already been used for the flat wave guide to draw the basic ideas of this theory such as for the patterned specific properties, the wave guide cut off, the propagation constant and the wave guide effective thickness. The American born Chinese scholar Tian Bingeng used the saw tooth form plane wave theory to derive a modular equation to handle the problems of the prism and grating coupler and surface scattering. Early, there was already theoretically attained a rigid explanation for the cross section circular and elliptically shaped medium wave guides. The question of the rectangular wave guide is more complex and there have emerged many approximate solutions such as the WKB solution method, the calculus of variations, Green's functions method and the effective refracting power method.

2. The gradual clarification of the material system and relevant technology. What materials do integrated optics use for manufacture? Which suitable techniques should it use? These are the first questions encountered in manufacture. In the last ten years, there have already been tested many finished film materials and finished film techniques. These materials are separated into glass, semiconductor, medium crystal, ferroelectrical bodies and organic substances. It is not only necessary for ideal materials to be made into film, their performance to be reliable and have excellent transparency but they must also have the multifaceted functions of the excitation of light, the modulation of light and the probing of light.

Up until now, although we still do not have a material that can satisfy the above mentioned requirements, yet research work has already become more focused on several types of material systems. One type uses an arsenic gallium compound for the bottom and the various functioning parts of the optical path all use an arsenic gallium compound or its ternary and tetrabasic compounds. To date, we have already used this type of material system to make the separate film components for lasers, modulators, deflectors and probes and we have also used it to trial produce simple integrated optical paths. This type of material system has one important flaw. In using an arsenic gallium compound material for

the light wave guide, transmission loss is relatively great (in the 0.8-0.9 micron wavelength, the loss is about 4 decibels/centimeter). Another type uses an arsenic gallium compound as the light source, uses a silicon material for the probe and uses lithium niobate, lithium tantalate or glass for the light wave and other multiwave guide devices such as the molded transformer, the modulator and the directional coupler. This is a type of mixed integrated material system and it brings into play the good points of various dissimilar materials and avoids their inadequacies. As a result, the estimated integration difficulty is smaller than the single piece and is easier to achieve. In recent years, another type was developed which used silicon as the base material system, and aside from the light source, the other wave guide device and probe could be made on the single piece integrated optical path.

Different materials use different manufacturing techniques. In optical path integration, all of the old techniques such as evaporation, splattering, diffusion, extension, photoetching and corrosion have found new applications. Yet, as mentioned previously, because the light wave must be shorter than the electromagnetic wave, technical demands for precision are even higher. Because of this, the original techniques must be improved and furthermore, it is still necessary to develop high precision techniques to accomplish the new tasks such as molecular beam extension, electron

beam exposure and holographic exposure.

3. The manufacture of various film optical components and the continual improvement of the performance.

The light wave guide. Various materials to make plane wave guide and various forms of band type wave guides such as the convex band type, covered layer band type, spine band type and repeated band type have already been used.

The coupler. Couplers transmit a light beam from one component to another component. There are many coupling problems encountered in the optical path such as light beam and wave guide coupling, wave guide and wave guide coupling, wave guide and light ray coupling and the coupling in various optical components. When light coupling enters the wave guide coupler efficiency can reach to 70%. The trumpet shaped wave guide coupler which goes from wide wave guide to narrow wave guide coupling has coupling efficiency of over 90%. Among the most important couplers made are the directional coupler and the wedge film coupler.

Modulation, switch and deflector. There has been research on various types of modulation effects and component structures using electricity light and magnetic light and studies on the electric

absorption effects of the modulation device. At present, the film modulator has already reached the functional stage. The use of the sound light effect has already been employed in prepared tests of light deflectors with lithium niobate and tellurium dioxide. In the lithium niobate wave guide, with the use of the simulated electric light prism structure, there has already been achieved the super fast deflection, switching and modulation of 9 light beams of information channels for each unit.

The laser. This is the key in integrated optical paths. It is not only a coherent light source but it can also be used to make nonlinear components and realize switch and logical functions. In view of preparation, the laser also has the greatest degree of difficulty in the optical path and is the most technologically complex. At present, film lasers still mainly use arsenic gallium/arsenic aluminum materials for their construction and there are five types of structures for those that have already appeared. They are the grating feedback type (including the scattered feedback laser and the scattering Bragg reflector type laser), the integrated double wave guide type, the integrated interference reflector type, the growth mesa type and the ring type. Among them, the scattering feedback type has already achieved continuous emission at room temperature.

The probe. A probe working under a 0.8-0.9 micron wave band is basically made of silicon material and arsenic gallium material. A probe operating under a 1.0-1.7 micron wave band is basically made of germanium and indium gallium arsenic phosphorous/indium phosphide material. The silicon probe is more advanced and at present, its response time is greater, in the millimicrosecond quantity level. The response time of the arsenic gallium probe can also be smaller than 200 millimicroseconds and its rising time can reach to under 1 millimicrosecond. This year the performance of the indium gallium arsenic phosphorous/indium phosphide probe has also been noticably raised.

Aside from the above mentioned components, there were also made the wave filter, model number transformer, double stable state component and film lens.

In the last few years, the focus of the great mass of research on integrated optics has been on according with the demands of a seperate film component but not much progress has been made in genuine integration work. Because of this, there are some people abroad who, when commenting on this situation, say that present integrated optics take "optics" as primary and "integration" as secondary. It can be expected that following advances in research work there will be the continuous arising of seperate components



with new and original forms, suitable structures and better performance.

4. Simple optical paths have been integrated by carrying out conscientious investigations of optical path integration. This work began in 1973. Up to today, simple optical paths of several different components or several similar component structures have successfully been integrated on the same base. For example, the Bell Laboratory of America has successfully integrated a laser wave guide and probe optical path on an arsenic gallium base. After the light beam produced by the laser in the optical path passes through 1 micron thick and 250 micron long passive wave guide transmission, the total differential transforming efficiency of the probe is about 10%. Also, for example, early, in 1976, the Japanese integrated six scattered feedback lasers on the same base and the light wave length interval of each lase was  $20 \pm 5$  angstrom and the spectrum width was about 0.3 angstrom. They passed through six passive wave guides and came into contact with a transmitted wave guide. After the performance of this type of integrated light source is further improved, it can become a multifrequency, repeat use light source for light communications.

There have been great achievements in research work on integrated optics, yet there are still many difficulties that await solutions.

For example, to have integrated optical paths function in light frequency bands as do the integrate circuits, the problem of the amplification of light must be solved. The performances of present material systems are still not totally ideal and when arsenic gallium is used for the light wave guide, transmission loss is still very great. As a semiconductor material, when the size of the component reaches the required smallness, there necessarily appear various boundary problems. Because of this, many boundary effects still await investigation. Technically, following the further advance of preparation work on integrated optical paths, the precision requirements become higher and higher and demands for stability and reliability also become stringent. Because of this, existing film forming technology must be further advanced and improved and even more the new technology of certain submicron level processes await perfection. At present, the performance of seperate components still cannot satisfy the requirements. When the laser is a key component its best form has still not been established, its stabilized operating life is still low and poor and its oscillating form still awaits research. Besides this, the prospect for many uses of integrated optical paths still awaits advancement and this advancement still requires the introduction and impetus of new ideas and new principles.

(3)

Which areas can the integrated optical paths be utilized in? This is a common question of concern. The tremendous motivating force of integrated optical path advancement foremost originates in its prospect for wide utilization.

The direction of the future use of optical paths is clear. If integrated optical paths are actually a highly developed form of the integrated circuit in the light frequency band, then its use in light frequency electron technology must be as infinitely resourceful as integrated circuits are in today's electronic technology. Yet, at present, integrated optical paths and light frequency electron technology are still in an initial period of development. Although some uses have already begun with better forms, yet the majority of uses still need to be strenuously developed and it is still necessary to search for suitable forms for specific uses.

Present research is the most quantitative, the future is the brightest and the forms put into effect and the sphere of its prospective uses has already pushed into light fiber communications. In the last several years, a great deal of research work related to integrated optical paths has been connected with light fiber

communications research and many of the names of the large scale international conferences have connected it with light fiber communications.

Below are shown the three main uses of integrated optical paths in light fiber communications: 1. the adoption of integrated technology and the film form to improve the specific properties of separate components in present light fiber communications systems (such as the laser, probe etc.); 2. to seek any new integrated optical path to substitute for certain separate components; 3. to combine with a single model light fiber to form a large capacity, long distance light fiber communications system.

There are three possible development stages for light fiber communications. The light fibers in the first two stages are all multipatterned and only the operating wave bands are different; one wavelength operating at 0.8-0.9 microns is the system widely used today; one wavelength operating at 1.2-1.6 microns is the one presently being developed and it is estimated that the system can be used in five years. In the development of these two stages, the development of integrated optical paths is shown by the improvement of the specific properties of the separate components and the seeking to make new optical paths to raise its reliability and performance. If it is said that in these two stages of development

that although the integrated optical paths have their good points, yet it is still not totally necessary, then coming to the third stage the integrated optical path becomes absolutely necessary. In the third stage of development, the system is composed of a single mode light fiber and integrated optical path and its operating wavelength has the lowest loss in light fiber. At that time, the system has tremendous communications capacity and fully utilizing this type of capacity it is then necessary to repeatedly use the frequency channel wherein there is the simultaneous transmission of a great deal of data in one fiber. To realize this one point, without the integrated optical path it is inconceivable because the core diameter of the single mode light fiber is very small (only several microns). It is necessary to feed the different data channels provided by the many optical paths to the fibers and the use of the stability and reliability required for the regular operation of separate components and system cannot be guaranteed.

The prospect for the use of integrated optical paths in handling optical data is evident and although this area of research has not developed much more than fiber communications, yet there have been some reports of application. For example, the American Naval Department used integrated optical paths to make a type of frequency analyzer which used the principle of the sound light effect. Light beams at different frequencies in a supersonic wave field can operate by deflecting at different angles. Many foreign

commentaries have pointed out that the development of integrated optics will definitely cause substantial gains in the handling of high speed signals and the mutual joining of the high speed digital computer's data generatrix.

The use of integrated optical paths to compose a light computer has really led people to look forward to the time when integrated optical paths are advanced. Theoretically, because the light computer uses high frequency light waves, operational speed could reach to 100 billion to 1000 billion times per second, memory capacity could reach to  $10^{18}$  and electronic computers cannot compare to it. Yet, it is regrettable that we still have not found a suitable technological form to realize this theoretical concept. Some people follow the structural form of electronic computer and try to use the integrated optical path to substitute for the integrated circuit to form various optical logical components. They also try to use the different states of rising and destruction to indicate "0" and "1" to form a light computer. Yet, the future for this method is full of frustrations because it has two inherent flaws. One is that its degree of integration cannot compete with and surpass that of the integrated circuit. As far as the quantum theory is concerned, the photons that pass in the optical path need to be much higher than the electron energy that passes in the electric circuit. The higher the energy the more

obvious the heating effect and the more outstanding the problem of the diffusion of heat. Because of this, theoretically integrated optical paths cannot reach the high degree of integration of integrated circuits. In reality, the surface of a crystal tube in an integrated circuit can already shrink to several square microns but the smallest surface of a laser in an integrated optical path can only attain to several hundred square microns. Secondly, it followed the electronic computers use of "0" and "1" to indicate the rising and destruction states of the electric circuit. Because of this, the light electricity mechanism is used and not the whole light mechanism. Originally, the optic handling of information had the advantage of "parallelism" whereby it adopted the Fourier transform and the information could be simultaneously handled and completed at one time. At present, the advantages of this type of concept has not played a role in optics and the light electricity mechanism not only creates a complex structure but also slows down handling speed. Therefore, although integrated optical paths began to guide people's futures, yet whatever is realized still needs to await further research and still needs to undergo much difficult work.

## THE LIGHT FIBER LASER GYRO

by Yang Xueyu

In 1913, Sagnick(?) brought forward the concept of the annular interferometer and attempted to use the optical method to measure rotating speed. In the apparatus for his experiment, he used a closed rectangular optical path and the two beams of light in the optical path broadcasted in clockwise and counter clockwise directions. When the optical path rotated, there were produced changes in the light range discrepancy of the two light beams and the combination of these two light beams formed an interference fringe. Based on the movements of the interference fringe, the rotating speed could then be measured. Yet, the sensitivity of this type of apparatus was very low. In 1963, the Sperry Corporation made a laser gyro model and its basic theory originated from Sagnick's(?) interferometer. Yet, it used a laser instead of visible light and employed the resonant cavity principle. The placing of a laser in the optical path caused changes in the frequency difference of the light range length and raised sensitivity. Yet, it used the existing closed phenomena of the resonant cavity



principle and because of this, recently there have been people who have renewed research and placed a laser in a passive cavity annular interferometer type light fiber laser gyro outside of a closed return circuit. By using light fiber for the optical path, sensitivity can be raised by going through the many circles of coiled light fiber.

#### Experimental Apparatus of the Light Fiber Annular Interferometer

Chart 1 shows the first light fiber laser gyro test apparatus successfully built in August, 1974 by Wally and Schosher(?) at Utah University. Based on Sagnick's(?) effect, the changes in the interference fringe are:

$$\dot{\Delta Z} = \frac{4AN}{\lambda C} \omega - \frac{4\pi R^2 N}{\lambda C} \dot{\omega} - \frac{2RL}{\lambda C} \omega$$

This is the light fiber gyro formula. In the formula, N is the number of wound circles of light fiber, R is the radius of the light fiber ring, L is the length of the light fiber, C is the free space light speed and  $\lambda$  is the length of the light in a vacuum. They estimated that if they use a 3 milliwatt helium neon laser, light fiber loss is 2 decibels/kilometer, L=4.3 kilometers and R=15 centimeters. Then the lowest measurable angle speed would be about  $3 \times 10^{-4}$  degrees/hour and has a great power of attraction

for explaining the light fiber gyro.

In 1976, Wally and Schosher(?) used an 85 meter long single mode quartz light fiber (diameter 4.4 millimeters, refracting power 1.457, loss coefficient 15 decibels/kilometer), the parameter of the apparatus was  $R=25.5$  centimeters,  $\lambda =6328$  angstrom and it attained the result of 3.85 radian/second/1 fringe. People at Stanford University using 50 meter long light fiber in a 10 circle winding speed revolving stage, in the same way, attained the results of one fringe per second in several radian. From this, we can see that when comparing the passive light fiber laser gyro and annular laser gyro, the insufficiencies are that sensitivity is low, output is of a nonlinear simulated volume and dynamic range is limited. To improve its properties it is necessary to bring in certain modulation technology.

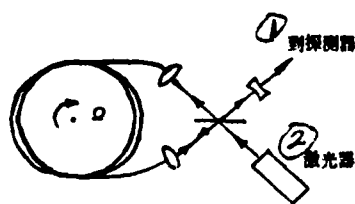


图1 第一个光纤激光陀螺示意图

Chart 1 Schematic Diagram of First Light Fiber Laser Gyro

1. To the probe
2. Laser

Usually modulation is carried out in the optical path by a nonmutual inversion component such as the farad component or sound light modulator.

#### 1. The Use of Farad Effect Modulation

As shown in chart 2, in a phase shift  $\pi/2$  area, the electric current rate of change is largest in the light electricity probe. Therefore, if there is a farad component placed in the optical path, this causes it to produce a fixed  $\pi/2$  phase shift which can raise sensitivity. Yet, the requirements for this  $\pi/2$  phase shift stability is relatively difficult to attain. One plan that has attracted people is the use of a farad component to provide a changing deflection phase  $\phi_b$  and no matter how the sensor rotates, the measured phase  $\phi$  on the probe has a constant value  $\pi/2$ . The rotating sensor is a zero position tracking apparatus which uses the phase shift brought in by rotation and the magnetic field electric current of the farad device for compensation. Under these conditions, the transformation function resembles the response of the farad deflection component in that it is basically linear. Moreover, the dynamic range is limited by the nonlinearity of the transformation function.

Because the use of the farad effect modulation plan is influenced

by the surrounding magnetic field, therefore there is disparity in stability. Further, because this type of apparatus has simulated output, this seriously limited the function of the apparatus and therefore it is rarely used.

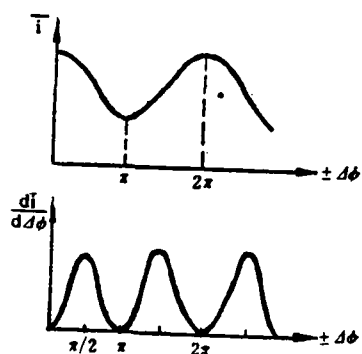


图2 相移 $\pi/2$ 处探测器电流变化率最大

Chart 2 The Change Rate of the Phase Shift /2 Probe Electric Current is the Greatest

## 2. The Use of the Sound Light Frequency Shifter

In 1978, Cashier (?) and Wade (?) of the United States Space Navigation Company, successfully developed a zero phase light fiber laser gyro as shown in chart 3. A light sound frequency shifter is inserted in the annular optical path. This frequency shifter causes the phase shift produced by the two beams of light to counteract the phase shift produced by the rotation and guarantees

that the two beams of light continuously maintain the same phase in the probe. The fringe movement caused by rotation is

$$Z_R = \frac{2LR}{C\lambda} \Omega,$$

and the fringe movement caused by the changes in the frequency shifter is  $Z_F = \Delta f \cdot nL/C$ . In the formula,  $n$  is the light fiber's refracting power. When  $Z_F = Z_R$ , because of the position of the fringe caused by rotation changes to compensate for the frequency shifter, the compensation quantity is  $\Delta f = \left(\frac{2R}{\lambda n}\right) \Omega$ . In this way, a relatively sensitive numerical output can be attained. Yet, its precision depends on the system's probing ability and the ability of the compensation fringe small position  $\Delta Z$ . The tests used  $L=100$  meter single mode quartz light fiber,  $R=13.5$  centimeters,  $\lambda=6238$  angstrom, the central frequency of the sound light modulation was 50 megahertz and the band width was 10 megahertz. Because of the influence of noise, the lowest measurable angle speed was  $\Omega_{min} = 0.5$  degrees/second.

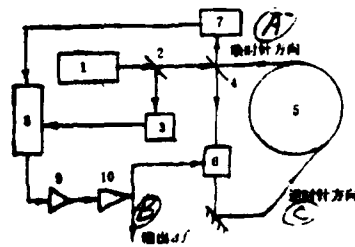


图3 零相位光纤激光陀螺示意图

- 1. 单频激光器
- 2,4. 分光镜
- 3,7. 探测器
- 5. 光纤
- 6. 移频器
- 8. 反馈系统
- 9. 积分器
- 10. 压控振荡器

Chart 3 Schematic Diagram of Zero Phase Position Light Fiber  
Laser Gyro

1. Single frequency laser
- 2,4 Spectroscope
- 3,7 Probe
5. Light fiber
6. Frequency shifter
8. Feedback system
9. Integrator
10. Pressure control oscillator
  - A. Clockwise direction
  - B. Output  $\Delta f$
  - C. Counter clockwise direction

Another type of sound light modulation plan in the light fiber annular interferometer uses electron phase position sensitive equilibrium heterodyne probe technology as shown in chart 4. When the laser frequency passes the sound light frequency shifter the change is  $\omega_0 + \omega_1$ , and afterwards divides and enters the two ends of the light fiber. The laser frequency emitted from the two ends of the light fiber has already induced the phase shift  $\phi$  produced by rotation. They divide with the  $\omega_0 + \omega_2$  mixed frequency of the machine's oscillation frequency, the medium frequency measured in the probe, and the phase shift  $2\phi$  detection and rotation speed proportion from the detector. In the experiments, there was used a 5 milliwatt helium neon laser, the 0.46 kilometer quartz single mode light fiber coiled to make a spiral tube with a diameter of 0.5 meters and the total revolving area was 58 meters<sup>2</sup> with a result of  $\phi = 7.7$  degree phase position/1 degree rotation/second. When the signal noise ratio was  $S/N=2$ , we could

distinguish 0.1 degree/second rotating speed.

Sound light modulation is relatively advanced and is much better than farad modulation. Yet, results of tests have always been limited by noise and thus it is necessary to lower the noise, including the noise induced by the light fiber, the noise of the light fiber coupling and the noise of the probe itself.

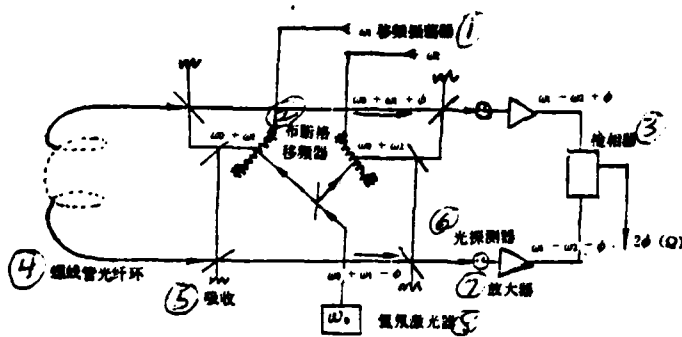


图1 采用平衡外差技术的光纤环形干涉仪示意图

Chart 4 Schematic Chart of the Use of the Balanced Heterodyne Technology Light Fiber Ring Interferometer

1.  $\omega_1$  frequency shift oscillator
2. Bragg frequency shifter
3. Detector
4. Spiral tube light fiber ring
5. Absorption
6. Light probe
7. Amplifier
8. Helium neon laser

## Error of the Light Fiber Laser Gyro

One of the error sources is double refraction in the light fiber. If a single mode light fiber coiled ring interferometer is used, in reality it is also the allowed transmitted perpendicularity polarization of the two modes of  $HE_{11}$ . The perpendicularity polarization of the two modes has minute speed error. Changes in temperature and in the machine influence the double refraction in light fibers and furthermore, just like the results produced by rotation, the induced phase shift causes the fringe to become confused. With appropriate polarization control, this error can be avoided. Even if the transmitted light is a polarized light, after light fiber transmission, the increased detector filter wave in front of the probe can then attain a stable fringe no matter how mixed the polarization is in light fiber transmission. This type of analysis can be extended to be used for multimode light fiber. Yet, although the two ends of the multimode light fiber are appended with polarization devices it can cause stability in the transmitted fringe. It can often greatly weaken light strength and even weaken the light strength of the transmitted fringe. Thus it is hoped that the polarization component contained in the light fiber will use a new type to maintain a polarization state light fiber (for example, the quartz single mode light fiber). Yet, actually this type of light fiber still has some remaining cross polarization and there



the polarization component is still needed. Generally, the problem of double refraction changes in the light fiber can be avoided.

Furthermore, fringe shifts are the linear coefficient of the light fiber ring radius. The size of the light fiber ring can change in accordance with the temperature. Although the widest possible use is made of compound materials to attain a relatively stable size, yet they are always able to produce a fixed error. The drift of the deflection component, the irregular function of laser power, the beam splitting ratio of the spectroscope and the instability of the probing component can all produce errors. However, these errors can pass through a computer program and attain compensation. Its final theoretical limit is the rotating speed's sensitivity limit which is determined by the scattered particle noise of the probe.

#### The Use of a Semiconductor Diode Laser as a Light Source

Loss in the light fiber ring channel mainly arises from the refracting power's unevenly produced scattering in the light fiber which is called material chromatic dispersion. Another source of loss is the surface scattering in the light fiber core and enclosure layer which is called conducted wave chromatic dispersion. Because material chromatic dispersion follows the increases and decreases

of the wavelength, it can, in long wave areas, prepare light fibers with very low material chromatic dispersion. In 1975, there was already found a light fiber material of zero material chromatic dispersion in the area of 1.3 microns. The chromatic dispersion of single mode light fiber nearly monopolized material chromatic dispersion and the influence of the conducted wave chromatic dispersion can be overlooked. Therefore, the use of the semiconductor diode laser, especially the  $\lambda=1.1$  micron double heterogeneous structured GaInAs P/InP diode laser, is extremely ideal. Tests have proven that identical types of fused quartz single mode light fiber with  $\lambda=6328$  angstrom and a light fiber loss coefficient of  $a_T=4$  decibels/kilometer, is one quantity level smaller than those that are  $\lambda=1.1$  microns,  $a_T=0.43$  decibels/kilometer. Furthermore, because the use of the diode laser is convenient for the use of integrated optics technology, this causes cost for the device to be low, the volume to be small and the weight to be light. Naturally, the use of the semiconductor laser can also produce a dependent system of moving wavelength and temperature which requires additional control.

Generally, present light fiber gyros still lie in a probed error source and there is still a distance between the development stage for raising the sensitivity and actual use. Yet, in principle, it avoids the induced and closed problems encountered by the mode of the common laser gyro. This basically provides a plan

with a great future. It not only is light in weight, small in volume and low in cost but even more, it ingeniously utilizes integrated optics technology. Furthermore, this instrument is a high level gyro with great potential. The angle speed error of several milliradian per second and the precision of a stochastic error of several milliradian degree angles per square root hour can be realized and used for prediction. Following the development of light fiber technology and the raising of the level of the probe component, functioning as an optical rotating sensor, the light fiber laser gyro must keep up with the common laser gyro. In certain uses, it can replace the annular laser gyro.

## PRESENT SITUATION OF THE LASER GYRO

by Fei Han

### 1. Survey

The laser gyro is a type of vital new inertial component. The conventional gyro is a mechanical meter which uses a high speed rotating rotor and relies on the inertia of substances. The laser gyro is then an inorganic movable component and is a type of optical electronic meter. Their power is the same as that of conventional gyros and both measure an objects angle speed and angle degree in relative inertail space. Publications opened up new vistas for gyro technology and also laid a foundation for a complete electronic inertial navigation system of an inorganic movable component.

The advantages of the laser gyro are that its life is long, its dependability is high, it does not require temperature control, its reaction is fast, it does not require demarcation, its surveying range is wide and its output is in a numerical form.

Because its performance is not influenced by the acceleration of gravity, vibration and shock, thus it is an ideal component for combined inertial guidance. Actually, all laser gyro inertial guidance use the combined form. The precision of present laser gyros has already satisfied the demands for aircraft navigation yet it is still inferior to the high precision of conventional gyros and its mass is also greater.

The first experimental laser gyro appeared in 1963. At that time Sperry Company of the United States made a 1 meter square laser gyro model and its lowest rotational speed was able to measure 50 degrees/hour. In 1974, the American navy used the A-7 plane developed by the Convair Company to test flight the guided missile which used a laser gyro guidance system. In 1975, the Convair Company successfully test flew a C-141 aircraft equipped with the Company's developed aircraft type laser gyro inertial guidance system. The results were that fixed position precision was 0.65 nautical miles/hour (probable error), speed precision was 5.5 feet/second and it was able to satisfy the demands for aircraft navigation. In 1976, the American navy representing the three armed forces signed a contract with the Convair Company for this company to design and manufacture an advanced development type laser gyro inertial guidance system as well as a production type laser gyro joined system to provide basic data for the system's dependability,

maintenance and performance in military surroundings. This caused the price of the laser gyro to decline from U.S. 30,000 dollars to under U.S. 4,000 dollars.

In November, 1978, the Boeing Company signed a contract with the Convair Company for the Boeing Company to make a Boeing 757/767 plane that used a laser gyro inertial reference system. Altogether, there were 1,200 platforms installed in 400 planes, each plane being equipped with three platforms. This shows that the laser gyro was put into production. This system satisfies the standard for the Arinc 704, is a complete functioning inertial guidance system which shows the longitude and latitude and is used for surveying the parameters of wind shear ground speed. Test precision on the test platform reached to 0.89 nautical miles/hour but the requirement suggested by the Boeing Company was 2.0 nautical miles/hour. The system's cost per platform was U.S. 40,000 dollars, its life span cost (including purchase price and maintenance cost) was lower than conventional turnable gyros and the first production type system will be delivered in 1981. Furthermore, laser gyro joined inertial guidance will be widely used in military fighter planes during the 1980's.

## 2. Basic Operational Principles

The structure of the laser gyro is fairly simple. Generally, in the structural material there are a triangular shaped light cavity and a triangular three apex design with a three sided reflector working to form a closed optical path. In this closed optical path, there are two transmitted beams of laser waves travelling clockwise and counter clockwise. (chart 1).

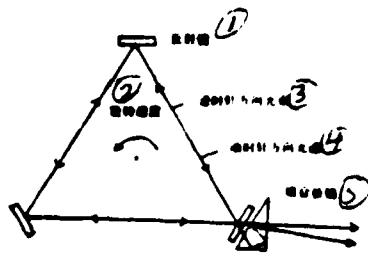


圖1 激光陀螺工作原理示意图

Chart 1 Schematic Chart of the Laser Gyro Operational Principle

1. Reflector
2. Rotating speed
3. Counter clockwise light beam
4. Clockwise light beam
5. Combined prism

The two laser beams are produced in this way: a vacuum is made in the cavity which is filled with a helium neon gas mixture and after the device's electrode gives electrode electrification there is set off two continuous laser beams. When the annular optical path

is motionless, the frequency difference of the two clockwise and counter clockwise beams of light is zero. If the optical path has clockwise rotation in the inertial space, then the clockwise light beam range becomes longer and the counter clockwise light beam range becomes shorter. This is because the resonant cavity only selects the integral number of times of wave length equal to the light of the closed optical path light range length. Because the light speed is constant, for the frequency difference produced in the two beams of light, the size of the frequency difference can be shown by the following formula:

$$\Delta f = \frac{4A}{C\lambda} \omega$$

In the formula,  $\Delta f$  is the frequency difference,  $A$  is the surrounding area of the optical path,  $C$  is the light speed,  $\lambda$  is the wavelength and  $\omega$  is the rotating angle speed. The frequency difference is measured in this way: the two beams of light pass through the optical device's combined production interfering fringe and then is transformed by the number and shift of the light sensitive diode inductive interference fringe into electric pulse output. Pulse speed represents rotation speed and the pulse number represents the turning angle of the laser gyro.

### 3. Several Typical Laser Gyros



A crucial problem in the development of the laser gyro is overcoming the so called locking phenomenon. Locking indicates that when rotational speed is very low, gyro output is zero. Furthermore, the nonlinearity of the gyro's characteristic curve in the locked area is critical so that when passing this area the repetition and linear degree of the characteristic curve is a very high straight line (chart 2).

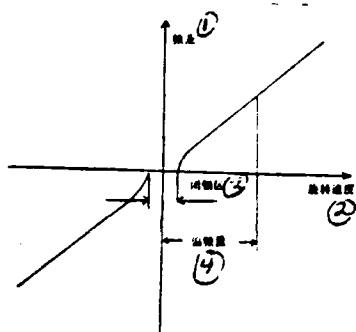


图2 闭锁和偏频

Chart 2 Locking and Deviation Frequency

1. Frequency difference
2. Rotational speed
3. Locked area
4. Deviation frequency amount

Locking is mainly due to the imperfect quality of the reflector, and besides reflecting, it also produces a small amount of scattering causing energy mutual coupling to occur in the two beams of light. The locking width is generally 10 degrees/second to 1 degree/second which does not satisfy precision demands. To eliminate

locking, it is necessary to shift the operating point of the laser gyro to a straight line section. The method for this is to increase the fixed rotating speed or light range difference on the laser gyro and also decrease it in output so as to attain a real rotating speed. This is usually called deviation frequency (see chart 2). There are many deviation frequency plans and the gyro type is also based on a deviation frequency plan. The following are the three commonly used plans:

1. Mechanical Vibration Method. This is one of the most practical methods used recently to resolve the problem of laser gyro locking. Recently developed high precision gyros all use this method. The technology of the mechanical device is relatively advanced and it is easily controlled, yet its drawback is that when the mechanical vibrations pass the locking area it can produce noise and cause the characteristic curve to change into a nonrigid straight line. The laser gyro developed by the Convair Company use this method of deviation frequency. The GG 1300 gyro developed by the company (chart 3) is at present the most precise laser gyro. The inertial guidance in test flights of the C-141 aircraft used this type of gyro. The circumference of this type of gyro is 43.4 centimeters and there is an optical cavity made within the CER-VIT ceramic glass material which is filled with helium neon gas. The optical cavity is then used to make an optical

path which also plays a role in the laser discharge tube. The laser wavelength is 0.633 microns. One side of the reflector is required to be spherical so as to benefit the alignment of the optical path. The structural piece is installed on a high Q value reverse spring and uses a piezoelectric component which produces vibration. The vibration rate is 100 hertz and the angle of oscillation is about 0.1 degree. The performance of the GG 1300 is: at zero deviation 0.01 degrees/hour, the random shift rate is 0.005 degrees/ $\sqrt{\text{hour}}$ , the proportion coefficient error is 0.005%, the resolving power is 1.57 angle seconds per pulse and the measured sphere  $\pm 400$  degrees/second. The laser gyro developed by this company also has a GG 1342 model with an optical path length of 32 centimeters, precision about the same as that of the GG 1300 and it is used for the inertia of the Boeing 757/767 and other aircraft inertial guidance systems; the GG 1328 model has an optical path length of 21.3 centimeters, is used in tactical weapons guidance systems and the navigation precision is 5 to 10 nautical miles/hour.

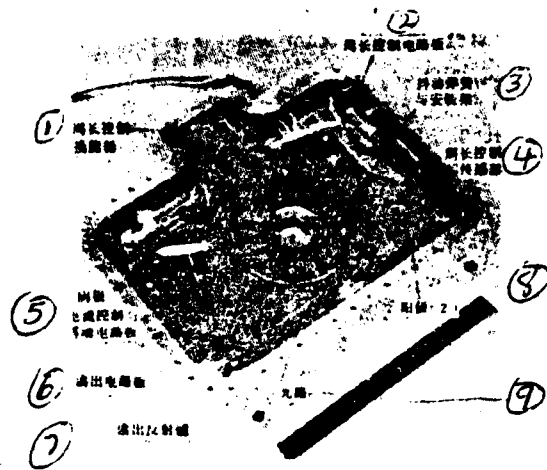


图3 GG1300 激光陀螺

Chart 3 The GG 1300 Laser Gyro

1. Circumference control transducer
2. Circumference control circuit plate
3. Reverse spring and installed stand
4. Circumference control sensor
5. Negative pole
6. Output circuit plate
7. Output reflector
8. Positive pole
9. Optical path

2. The use of the transverse Kerr magneto optical effect, also called the magnetic mirror method, is the use of one sides special magnetic reflector to cause clockwise and counter clockwise light beams and after producing different phase delays there is reached the goal of deviation frequency. A typical example of the use of

this type of method is the SLIC-7 laser gyro developed by the Sperry Company. A schematic diagram of its optical path is shown in chart 4.

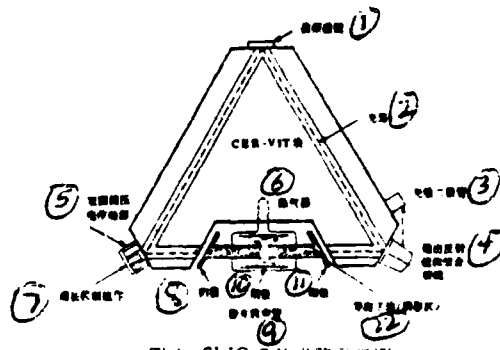


图 4 SLIC-7 的光路示意图

Chart 4 Schematic Diagram of SLIC-7 Optical Path

1. Deviation frequency magnetic mirror
2. Optical path
3. Light sensitive diode
4. Output reflector and combined prism
5. Double feed piezoelectric operating apparatus
6. Degasser
7. Circumference temperature control component
8. Positive pole
9. Laser discharge tube
10. Negative pole
11. Positive pole
12. Plasma (shadow area)

It has a three sided reflector: one side is used for optical path circumference control, one side is the output reflector and one side is the magnetic mirror. For the magnetic mirror, first a

ferromagnetic metallic material (presently changed to using a more effective garnet) film is applied on the basic section and afterwards there is again applied a layer of medium film so as to attain the high reflection power and suitable deviation frequency for the gyro. The random shifts of the deviation frequency can pass the exerted alternating electric current of the magnetic field coil causing the elimination of deviation frequency periodic reversal.

The circumference of the SLIC-7 is only 19 centimeters and it uses a structural block and laser discharge tube separated modular structure. The discharge system's metallic and pyrex glass joined component used glass and metallic sealing techniques, the inside was filled with helium neon gas and the operating wavelength was 1.15 microns. Actually, the SLIC-7 contains three gyros which are fitted on a CER-VIT ceramic glass piece. Its optical path is interwoven, its sensitive axes are perpendicular and thus the structure is very compact. The diameter of the entire apparatus is 10.2 centimeters, its height is 11.4 centimeters and its weight is 2.27 kilograms. The SLIC-7 is mainly used in tactical guided missile guidance and its performance is: at zero deviation 1.0 degrees/hour, random shift rate is 0.13 degrees/hour, proportional coefficient error is  $250 \times 10^{-6}$ , resolving power is 6.6 angle seconds per pulse, the measured sphere is 1000 degrees/second,

reaction time is 250 milliseconds and it can bear 400g acceleration.

The advantages of the magnetic mirror method are that the structure is simple and there is no mechanical vibration and therefore the three gyros can be inserted and installed to form a module. Its drawbacks are that the magnetic mirror increased optical path loss and must use 1.15 microns as the operating wavelength which decreased the refracting power. Moreover, the specific properties of the magnetic mirror are not easy to control and therefore, at present, its precision is inferior to that of the mechanical vibration method. Aside from this, the magnetic mirror method must also use the electromagnetic vibration method to pass the locked area and therefore has the same problems as the mechanical vibration passing the locked area.

3. The Differential Laser Gyro. This plan was brought forth in 1968 by the Hamilton Company of the United States. A polished quartz crystal is installed in the gyro's optical path and causes the crystal's optical axis (Z axis) to follow the light beam direction. An electromagnetic coil is wound around the crystal and the optical function and Faraday effect cause the production of four types (the left circle polarization is clockwise, left circle polarization is counter clockwise, right circle polarization is clockwise, right circle polarization is counter clockwise) of light

beams which is equal to having gyros moving in the same resonant cavity. After the output of the two gyros decreases, total output sensitivity is twice that of a single gyro, the deviation frequency is properly counteracted and thus the demand for deviation frequency stability can be lowered. At the same time, the error induced by all of the surrounding elements is eliminated. The size of the differential laser gyro made by the Hamilton Company is 17.8 centimeters x 16.5 centimeters x 5.1 centimeters, it uses a ULE ultralow expanded titanium silicate block as the structural element, its optical path is 8 digits, it has a modular structure, its laser discharge tube is made entirely of quartz and the two ends are radiation protected multicoated quartz windows. Its performance is: shift stabilization is 0.05 degrees/hour ( $1\sigma$ ), resolving power is 1.6 angle seconds per pulse, measured sphere is  $\pm 1000$  degrees/second and it can sustain 16g acceleration. The good points of the differential laser are that it does not have any form vibration and thus according to theoretical analysis its linear degree is good, noise is small and it can attain to 0.001 degrees/hour precision. Yet, because at present its optical path is complex, it is necessary to install an optical device with a 1/4 piece and a polarization light filter piece. Also because loss is great and performance is not easy to control therefore its precision is still inferior to the mechanical vibration type.



#### 4. Problems Encountered in Manufacture

##### 1. Applied Film of the Reflector

The scattering of the reflector, besides causing locking, can also decrease laser gyro precision. Research has shown that 0.0005% scattering can cause the error of laser gyro performance to reach 0.07 degrees/hour to 0.3 degrees/hour. Because of this, it can be said that the greatest technical key for present laser gyros is the raising of the quality of the reflector. The reflector used by the laser gyro is a multilevel medium film reflector. It requires the selection of a base piece and film material and significant research for the system's base piece manufacture and polishing applying film technique and testing to determine the most suitable coating technique (selected from the electron beam evaporation and splashing methods) for the multilevel medium film and fixing the technical parameter of the deposition film (for example, the deposition film, the base piece preparation and temperature, the electronic medium material preparation before evaporation and the remaining gas pressure).

##### 2. Shift Produced by Larmor Flow

This type of effect is similar to the constant shift of conventional gyros. It arises from the electric current of the energy provided by the functioning of the gas laser and is related

to the movement of the discharge gas in the plasma. It is not related to rotation as it cannot be overcome. It can cause an apparent shift of several hundred degrees per hour. At present, we have already adopted the use of a central negative pole and split positive pole structure and the regulation of the total electric current and the electric current of the two branches can resolve this problem. Yet, we are still unclear about its error mechanism. The demands for the electric current regulator are: the total electric current should be regulated to 0.1%, the differential electric current of the two branches should be regulated to 0.01%. Further, a vacuum must be formed in the housing so as to prevent gas movement. It is also necessary to pay attention to the discharge tube temperature distribution.

### 3. Circumference Control

The laser gyro circumference following the temperature changes can produce errors. Because of this, it is necessary to decrease the laser gyro's temperature sensitivity and raise the zero deviation repetition. It is first necessary to select and use a material with a very low heat expansion coefficient to make the structural block. This requires that the heat expansion coefficient be smaller than  $0.3 \times 10^{-7}$  meters/meter  $1^{\circ}\text{C}$ . At present, abroad there are two types of material suitable for making a laser gyro structure block. One is CER-VIT ceramic glass manufactured by the Owens Company and the

other is the ULE material (the ultralow expansion coefficient titanium silicate material which is a type of manmade, noncrystalline isotropy quartz glass) manufactured by the Corning (?) Company. These two types of material both satisfy the above mentioned demands of a low heat expansion coefficient. Yet, they are very hard and therefore require the use of supersonic mechanical methods for processing. Besides this, it also requires passive control (temperature compensation) and active control (closed ring regulation) of the optical path circumference. According to reports, it is necessary to cause gyro precision to reach 0.01 degrees/hour and the circumference should be controlled to a wavelength of 0.1%.

#### 4. Life Span

During the initial period of laser gyro development there was encountered the problem of a short life span and this caused the electric current in the laser to increase at any time and finally to break down. Later, it was discovered that the reason was helium neon leakage so that the gas was contaminated by the sealed material escaping gas and the negative pole absorbed gas and the optical surface deteriorated. They could adopt a structural block material, improve the design, improve the sealing technique (such as using optical glue) and adopt measures for the coating technique of the reflector to raise the life span. In the gyro gas storage room there is usually designed a degasser and before filling it with

helium and neon the degasser must be heated in the vacuum to eliminate the remaining gases. According to reports, the Autonadics (?) Company when developing a laser gyro process, to effectively eliminate the gas, utilized radio frequency washing and vacuum baking. After the use of these measures, the life span of present laser gyros is estimated to be able to reach a minimum of 20,000 hours.

#### 5. Application

Because the dynamic sphere of the laser gyro is wide (it can measure an angle speed of 0.01 degrees/hour to 2,000 degrees/second, the dynamic sphere is greater than  $10^8$ ), thus its application sphere is extremely wide. Aside from being used in the joined inertial guidance of aircraft, it can also be used in tactical guided missile guidance, in the inertial guidance of atmospheric mobile warheads, in aircraft course and pose reference systems, in ship based stabilizing platforms and space aircraft.

The American airforce is in the process of carrying out a multifunctional inertial reference module (MIRA) plan and the developed joined inertial module can satisfy the demands of flight control navigation and weaponry for fighter planes and transport planes. For the inertial module, the use of laser gyros and power tuned gyros was considered. According to reports, the performance

of the laser gyro is better than that of the power tuned gyro, yet its mass is larger.

The American navy is in the process of testing the Convair Company's laser gyro inertial measuring device. Its external form and function are interchangeable with the inertial measuring device of the AN/ASN 92. After this system operated for 1,100 hours (including several tens of hours test flights on the F-14 aircraft), there occurred the first breakdown. The crystal tube in its demarcated storage went bad. Before this, the system did not require any renewed demarcation or maintenance. According to reports, the navy's next generation of ship based aircraft inertial guide systems will use the joined system of the laser gyro.

Tactical guided missile guidance has a lower laser gyro precision requirement which is usually about 1 degree/hour. Although the aircraft course and pose reference system can use the laser gyro still it is estimated that because the cost is high, in this respect it does not surpass the low precision conventional gyro.

#### 6. Development Trends

Recently, the United States, England, France and the Soviet Union have all energetically developed laser gyros and focus has been on its development as an inertial component.

At first, there were only two American companies that manufactured the laser gyro, Sperry and Convair, but now this has expanded to ten companies. The Convair Company has already built a 409 meter<sup>2</sup> plant and its monthly output of laser gyros can reach to 300. At present, they are already manufacturing 30 per month.

Recently, the famous Leeding(?) Company is manufacturing the LTN-90 inertial guidance system in order to handle conventional gyro aircraft inertial guidance. This is a civil aircraft which uses a laser gyro joined system and it is estimated that it will be finished in 1980 and put into operation in 1981. The Leeding (?) Company's gyro is not like the majority of laser gyros which use a triangular optical path. Rather it uses a square return circuit and according to reports, this type can save time and raise measuring precision. This type of gyro can also use the mechanical vibration method. This company believes that the joined inertial system can become standard equipment for many civil aircraft and it is estimated that in the next 15 years the total demand will be about 4,000.

The Carfut(?) Company has already begun test flights of the laser gyro inertial guidance system in their aircraft and based on reports, precision is better than 3 nautical miles/hour. This type

of laser gyro also uses the mechanical vibration method to prevent locking.

Britain's Felundy Company and the Sperry Gyro Company have already obtained a contract from Britain's Ministry of National Defense which wants them each to design, manufacture and supply laser gyro inertial guidance systems. These two companies have independently carried out development for three years and their developed systems have all been test flown. The gyros of the two systems both use triangular optical cavities with each edge length being 15.2 centimeters, both use magnetic mirror deviation frequency and the angle speed is able to survey about 0.02 degrees/second. The largest angle speed is 400 degrees/second. The Sperry Company estimated that the cost of the laser gyro is double that of the conventional gyro, yet because its dependability is high its maintenance cost is one tenth to one quarter that of the conventional gyro.

The Calui(?) Company and SFENA Company of France formed a partnership to develop the Sextan laser gyro inertial guidance system used in helicopters. This is a combined Doppler radar joined system. The entire system's weight is 30 kilograms, its total navigation precision is 1 nautical mile/hour and it was originally scheduled to be test flown at the end of 1979. The laser

gyro used by this system is the J102AAM model developed by the SFENA Company. Its main characteristics are: the helium neon laser operating wavelength is 0.63 microns, it uses mechanical vibration method deviation frequency, it has a circumference control return circuit, its resolving power is 3.2 angle seconds per pulse, its shift rate is about 1 degree/hour, its measured sphere is above 250 degrees/second, its total size is 12.2 centimeters x 14 centimeters x 5 centimeters and its weight is 1.5 kilograms. At present, this system is in the preproduction stage and it is estimated that full production can begin in 1981.

The SV2 Company hopes that by the end of 1984 it can produce a laser gyro full inertial reference system with precision reaching 1 nautical mile/hour. According to reports, the SFENA Company is in the process of extending its factory in the Puodai(?) region. Its extended area is 1,500 meters<sup>2</sup> which is used to manufacture laser gyros. At present, their production rate of laser gyros is one per month and based on need it will reach to over 30 per month.