Neutral ion beam sputter deposition of high-quality optical films

By Austin Kalb

The newest generation of high-accuracy ring laser gyroscopes (RLG) requires state-of-the-art optical coatings. The process of neutral ion beam deposition, developed in the last 10 years for the RLG application, has met this challenge. The optical properties of the mirrors in the RLG affect gyro performance in a number of different ways. This article briefly discusses the relationship between mirror properties and gyro performance, and then describes the coating process of neutral ion beam deposition. The measurements required to develop this coating technology are described in the context of the advancement of the coating technology.

Gyro performance

First and foremost, scattering of the incident laser light by the coating causes a phenomenon known as lock-in. The scattering causes the clockwise and counterclockwise beams of the RLG to couple together. At low rotation rates the two beams become locked in frequency, and the RLG ceases to produce meaningful output. Furthermore, near the lock band, severe scale factor (the scale factor is defined simply as the gyro output for a given rotational input) nonlinearities occur. Figure 1 shows the lock band at low rotation rates, as well as the scale factor non-lineari-

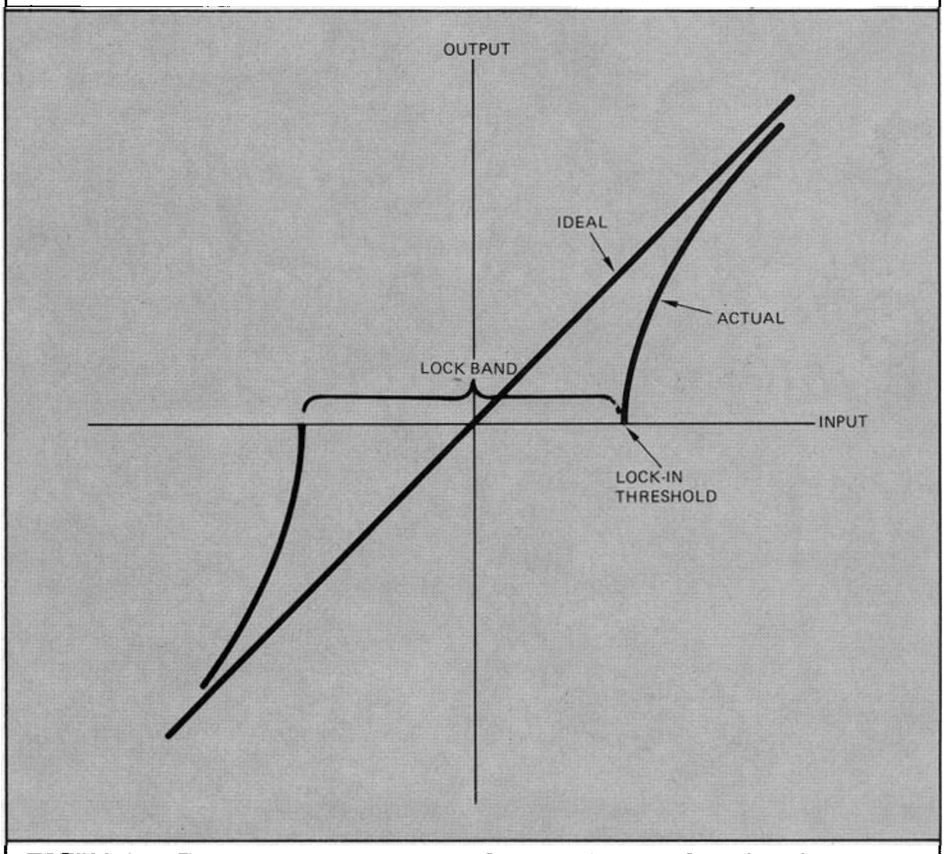

FIGURE 1. Gyro output vs. rotational input showing lock band caused by mirror scatter.

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ties near the lock region. For high accuracy RLG applications the scatter coefficient ($I_{scattered}/I_{incident}$) must be below one part in 10^6, or 1 ppm.

Another issue is the absorption of the incident radiation in the multilayer stack. This affects the RLG by decreasing the cavity Q. The lower cavity Q results in a broadened laser linewidth. The effect on gyro performance is an increase in white noise. Typical requirements for high accuracy RLGs set absorption at or below 20 ppm.

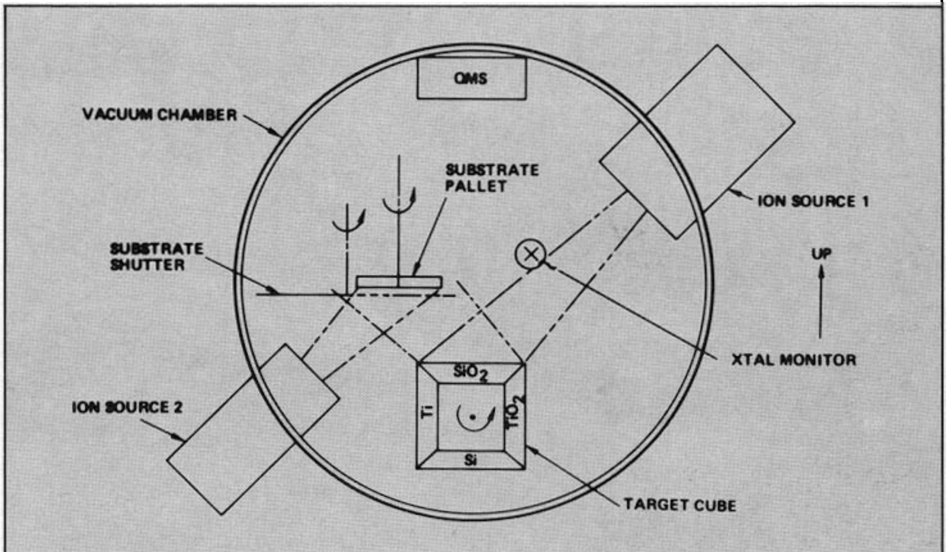

FIGURE 2. Schematic representation of ion beam deposition system.

Coating requirements

Coatings for RLG use must have stable optical and mechanical properties. The mirrors are subject to a number of cleaning and processing steps in the assembly of the laser gyro. Physical degradation due to this handling is unacceptable. Changes in optical properties during gyro operation lead directly to poor performance. Before shipment, RLG systems undergo extensive qualification. During this qualification, numerous system parameters are determined that are subsequently used to convert raw gyro output data into meaningful navigation data. Changes in coating performance affect these parameters and lead to errors in the system output.

Although commercially available E-beam coatings can meet all of the individual requirements for high accuracy RLG use, it is unfortunate that all the requirements cannot be met simultaneously. Typically, to achieve low levels of optical absorption in E-beam coatings, the substrates must be heated during the deposition process. This leads to crystallite formation in the films, drastically increasing optical scatter. While E-beam coatings are mechanically adequate for RLG applications, optical degradation in the laser gyro operating environment is a major problem. Increases in total loss, where total loss is defined as 1 − reflection (or as absorption + transmission + scatter), are believed to be due to exposure to ultraviolet radiation produced in the helium-neon plasma. This UV-induced degradation can destroy a gyro in a matter of hours. This degradation mechanism is usually an order of magnitude more serious in E-beam produced coatings than in those produced by the ion-beam deposition process.

Ion beam coating at Rockwell

The ion-beam deposition process has been independently developed by a number of RLG manufacturers. The system developed at Rockwell consists of a ultra-high vacuum (UHV) chamber fitted with two Kaufman-type broad-beam ion sources,[1] originally developed for space propulsion. It is housed in a Class-10 clean room to reduce contamination from airborne particles. In conjunction with the deposition system, an elaborate state-of-the-art optical measurement facility has been developed.

It is important to stress that this measurement facility plays an integral part in the coating development process. In order to develop coatings that perform in the desired range, one must be able to measure optical performance in that range. Until now measurement systems capable of measuring optical parameters in the ppm range were not commercially available.

The process of ion-beam sputter deposition (IBSD) consists of sputtering a high-purity metal target in the presence of oxygen gas, thereby producing metal oxide films. The target material is sputtered by a Kaufman-type broad-beam neutral ion source. Typically, the primary ion beam consists of high-purity argon. A second ion source, aimed directly at the substrates, is used for substrate precleaning as well as film modification during growth. A schematic representation of this configuration can be seen in Fig. 2.

A typical process sequence consists of loading the cleaned, uncoated substrates in a UHV system and pumping to at least 10^{-8} torr. The purpose of the UHV system is to keep potential contaminates from material outgassing at an absolute minimum.

After a suitable base pressure is reached, an orderly start-up sequence is initiated. This consists of a process gas purge followed by an ion source warm-up. The substrates are then briefly sputter cleaned, and the targets presputtered. The deposition process consists of alternately sputtering a silicon and titanium target in the presence of approximately 10^{-4} torr of oxygen. The thickness of each layer is measured by a quartz crystal monitor.

A typical stack consists of 12 or so layer pairs. In most applications the thickness of each layer is one-quarter wave optical thickness at the design wavelength and angle (i.e., the wavelength and angle for which the optical stack is tuned). This is 6328 Å, and 45 deg for a square helium neon laser gyroscope.

The mirror coatings are a critical part of the laser gyro; thus no expense is spared in the quality of the materials and processes utilized. Target materials are the purest available, typically 99.9999 percent pure, with a minimum of harmful impurities such as the color center forming transition metals. Process gases are also the best available. Special high-purity gas bottles and regulators are used, and gas lines are specially prepared by a chemical/mechanical process.

The entire deposition process is computer controlled; distributed intelligence is utilized to avoid down time associated with a single component failure. The process is completely automated and can proceed to completion without operator intervention. Presently, however, data logging is still done the old-fashioned way—by hand.

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Optical measurements

As indicated earlier, the development of fast, sensitive optical measurement techniques is of prime importance in the development of IBSD for RLG applications. Before the advent of this new measurement technology, only the visible spectrophotometer was available for the measurement of absorption loss and transmission. While it is a good tool in the development of low-quality coatings, the spectrophotometer is severely limited in RLG applications. A good spectrophotometer has an intensity resolution of about 0.05%. Since RLG coatings have transmissions below 0.01%, this is clearly inadequate. Thus, in addition to the development of IBSD, an equal emphasis has been placed on the development of measurement techniques.

Early in the development of IBSD for RLG applications, Sanders[2] invented a device with a measurement resolution of about 25 ppm (0.0025%). The mirror in question was inserted in a laser cavity with a fixed, known gain-to-loss ratio. A Brewster window was then introduced into the cavity, and its insertion loss varied until the laser extinguished. By knowing the loss of the Brewster window, the total loss of the test mirror can be determined. The test setup was rather clumsy and sensitive to changes in gain due to cavity alignment. Further developments, such as dual Brewster windows to correct beam offset, provided a temporary fix until better techniques were developed.

Another popular technique, still utilized somewhat today, is based on the linewidth of a passive resonant cavity. The test mirror is made part of a three-mirror cavity, with two other mirrors of known total loss. A probe laser beam is injected into the cavity and swept in frequency through the test cavity resonance. The output of the test cavity is recorded, and the full width at half maximum of the cavity output determined. A simple calculation, based on a Fabry-Perot type system, leads directly to the value of the cavity Q, which can then be easily converted to a round-trip cavity loss. The values of the known mirrors are subtracted from this value, and the total loss of the test mirror is determined. This technique works well with high loss cavities, where the linewidth is very broad. As the mirror deposition process was further developed, and cavity losses decreased, the technique began to be plagued by errors associated with thermal noise, as well as the speed and repeatability of the frequency scan.

This technique will require improvements if it is to remain useful in the future, since lower loss coatings decrease the sensitivity and resolution of the measurement results.

A few years after Sanders, Herbelin[3] provided the basis of a new measurement technique. Again the test mirror is used in a resonant cavity. A laser probe beam, inject-

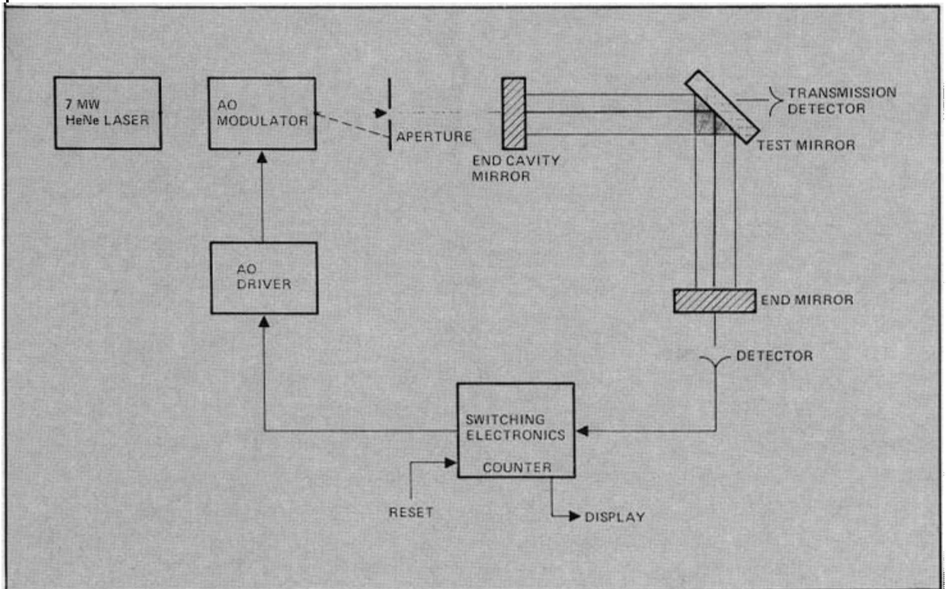

FIGURE 3. Schematic representation of ringdown lossmeter.

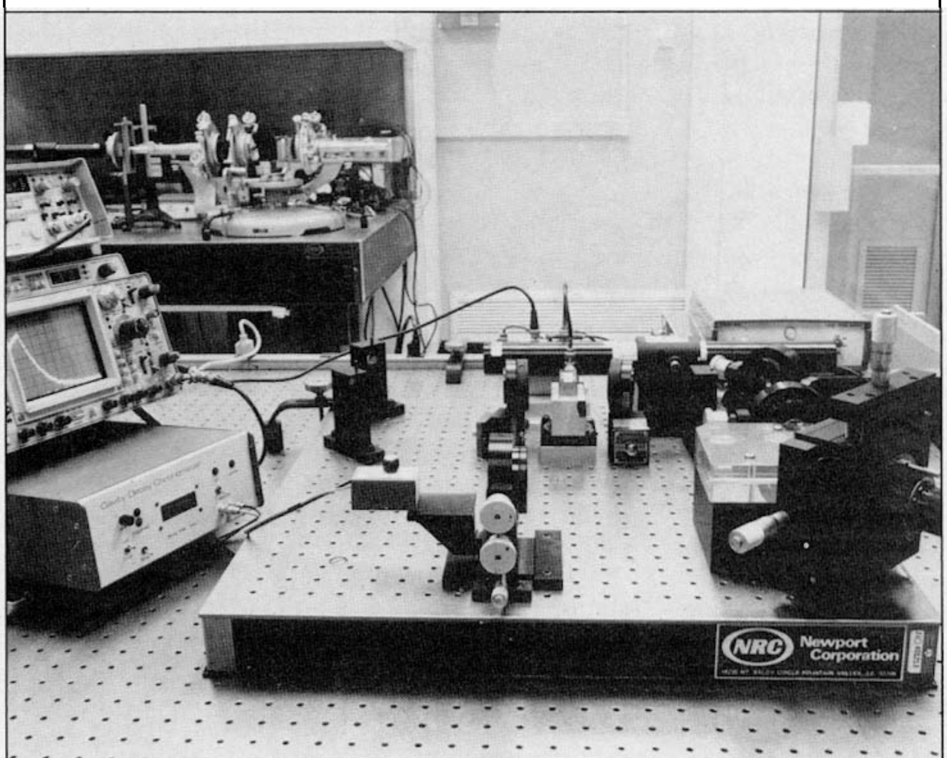

FIGURE 4. Photograph of ringdown lossmeter. The ringdown curve can be seen on the oscilloscope in the upper left.

ed into the cavity is monitored and the phase difference between the input and output beams measured. As the cavity losses decrease, the incident light spends more time in the cavity, and the phase difference increases. The resolution of this technique is around 10 ppm, sufficient for most RLG applications.

One of the problems associated with this technique is the difficulty of making an accurate optical phase measurement. Furthermore, there are complications associated with controlled amplitude modulation utilizing a Pockels cell, which requires a high-frequency, high-voltage input.

Recently, Anderson[4] developed a technique similar to Herbelin's in which a probe beam is inserted into a resonant cavity. When the cavity is clearly in resonance, the beam is abruptly switched off. The cavity decay is monitored on a digital storage oscilloscope, and the photon lifetime in the cavity determined by the slope of this decay. A schematic of this technique is shown in Fig. 3, and a photograph of the experimental setup is shown in Fig. 4.

The technique utilizes an acousto-optic modulator to switch the beam, avoiding problems associated with high voltage ac modulation. As the cavity losses decrease, the photon lifetime in the cavity increases, increasing measurement sensitivity and resolution. For production usage, the decay time can be calculated electronically and the operator need only convert this time to a loss value by a simple formula. This technique is compatible with further mirror coating development and is the one currently in use at most RLG manufacturers.

Transmission of the optical coating is usually determined by a direct measurement. A linearly polarized He-Ne laser is incident on the test mirror at the design angle, and the transmitted intensity is measured using a 6-decade calibrated power meter. The ratio of the transmitted intensity to the laser intensity gives the intensity transmittance directly. After a single mirror is measured, it can be used as a reference, avoiding the problem of a calibration drift over the 6 decades. The photon lifetime apparatus described above can also be utilized to measure transmittance. This technique has proven to be extremely repeatable and reliable, and is currently in use as the industry standard.

The last optical measurement of importance in the RLG mirror is the scatter coefficient. Two classes of scatter can be distinguished. Background scatter is associated with substrate surface roughness and film crystallite formation. Discrete scattering centers are associated with point defects such as particulate contamination in the film. Background scatter is measured in a fashion similar to the transmission. A linearly polarized He Ne laser beam is incident on the test mirror. The transmitted and reflected beams are discarded, while the scattered light is collected, usually by a hemispherical integrating sphere. Low light levels are typical, so a photomultiplier tube is usually used to measure the scattered light intensities. Again, a simple ratio of scattered to incident light gives the scatter coefficient.

Discrete scattering centers are measured in a similar way except the test mirror is scanned by the incident beam and a map of discrete scattering centers produced. This map is then used by gyro assembly personnel to locate the mirror on the gyro, such that the laser beam strikes a spot where no discrete scatterers are present.

Film properties

Multilayer films produced by IBSD meet the current requirements for high-accuracy RLG applications. Typically, the complex indices of refraction of the materials used are $(1.46 + 5 \times 10^{-6}i)$ for silica and $(2.4 + 1 \times 10^{-5}i)$ for titania. This corresponds to an optical absorption for a 25-layer stack of about 0.0030% (30 ppm). Transmission is adjustable by varying the total number of layers.

On smooth substrates, background scatter is around 1 ppm. Discrete scattering centers are minimized by careful cleaning and handling. A part suitable for RLG use will show less than 5 discrete centers over the entire coated region.

Mechanically, the parts are extremely hard and can withstand the elevated temperatures associated with gyro processing and operational specifications. Although hardness testing on thin films is difficult, Mho hardness testing (a simple scratch test) yields a value of approximately 7 for fused silica films. This is precisely the theoretical value. Adhesion of the film to the substrate is stronger than the glass itself. In adhesion pull tests, the glass substrate usually fractures before film-substrate delamination occurs, leading to a value in excess of 7500 psi.

Chemical analysis of the films by surface techniques such as electron spectroscopy for chemical analysis (ESCA) and secondary ion mass spectroscopy (SIMS) has shown the presence of minor impurities. Aluminum, carbon, and alkali metals have been found in the ppm levels. These are believed to originate during the deposition process and from the substrate materials. The films are amorphous according to x-ray analysis, and they show little or no structure under examination by the transmission electron microscope at a magnification of 120,000 X. The films tend to crystallize at temperatures above 300°C. This crystallization is clearly visible in the light microscope, and evident in x-ray diffraction analysis.

The future of ion-beam coating technology

The development of IBSD technology will likely continue as RLG manufacturers push for more accurate and smaller instruments. Furthermore, new applications for IBSD are rapidly emerging. Among the most exciting is the use of IBSD to produce highly damage resistant coatings for high-energy lasers. For example, the free-electron laser, operating between 500 and 1000 nm, is ideally suited for utilization of IBSD coatings. Laser damage at these wavelengths is known to be driven by optical absorption, thus the low absorption coatings produced by IBSD are well suited for this application.

Recent results at the shorter wavelengths also look very promising. In conclusion, ion beam sputter deposition is a relatively new and exciting coating technology and promises to stay that way for a long time to come.

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