Design and Development of Optical Coatings on Laser Bar Facets

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ABSTRACT

There are a variety of optical coatings needed on laser bar facets to make them functional. There are also several different types of laser bar facet materials to be coated which complicates the problem a little bit. These coatings fall into three types; antireflection coatings, high reflectors and partial reflectors. A wide range of coating designs and materials to be used in the coatings has been studied.

The anti reflection coating (AR) typically used is either a single layer coating, obviously consisting of one material, or dual layer coatings consisting of two materials. There are a limited number of applications that may involve larger number of layers if more than one wavelength or a wavelength band of more than 40 nm needs to be covered. The single layer coatings usually do not provide very low reflectance. Dual layer coatings provide the ability to design coatings with very low reflectance. Manufacturing process limitations allow for producing AR coatings with a residual reflection in the 0.1% - 0.2% range. Although lower reflecting coatings can be designed, process control parameters and optical measurement problems limit the coating manufacturer to this rang with $R \leq 0.2\%$ being a standard specification. This paper will discuss the various coating designs for achieving low reflectance on InP and GaAs laser facets and the optical measurements problems.

High reflectors are relatively easy to design. There are a variety of material choices available. One choice (Si/Al_2O_3) when applied for wavelengths below the absorption edge of silicon will result in a limit to how high the reflectance can be made. The use of non-absorbing materials will allow the reflectance of the coatings to be increased to the 99% range. The performance of various designs will be shown on different laser facet materials.

Partial reflecting mirrors 90/10 (R/T), 95/5 and other combinations can also be designed. These designs are used where the smaller transmitted signal can be used as a signal for controlling the cooling of the laser facet. Although these design are similar to the design of the high reflectors, using a symmetrical structure concept makes these coating easier to design and to trim into performance requirements. These designs will also be presented and discussed.

1. INTRODUCTION

As indicated in the abstract, we will be discussing the design of optical coatings on laser facets for a variety of applications. The optical properties of the materials used in designing and the manufacturing process are typically well known and published. However the process conditions used in various coating systems may vary as a result of the construction of the system or deliberate variations in controlling deposition conditions. These differences can result in variations from values as published. When designing these coatings it is critical that one uses the optical film characteristics resulting from the coating system that will be used to fabricate the devices. Therefore it is essential to characterize the optical properties of the films using deposition conditions that will be used in the manufacturing process. Most organizations that make these devices have techniques to measure the optical properties of films. One of the most popular techniques is VASE (variable angle spectroscopy) and information on how to do this is available from the manufacturer of the equipment. Optical coating houses may or may not have ellipsometers. However they will have spectrophotometers, which are used to measure the reflectance and transmission of films as a function of the wavelength. This data can be used to extract the optical properties of the films. This can be done by simple mathematics as published by Morton [1,2]. An alternative method would be to use any one of the thin film design programs that are commercially available. These usually have a procedure for entering measured data to extract the optical properties of optical film materials.

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We will also show a typical configuration for an E-beam evaporator coating machine with ion assist that can be used to coat the opposite faces of a laser facet in a single pump-down. We will then compare measured results for some of the coating designs. One of the problems in verifying the spectral performance of antireflection coatings on laser facet materials is the use of thin wafers as witness samples for spectral measurements. The cause of this problem and the solution will be discussed.

2. DESIGNS

Single layer AR

The most common laser facet materials are InP and GaAs. These two materials have a fairly high refractive index and can be perfectly antireflection coated with a low refractive index material equal to the square root of the refractive index of the laser facet at that particular wavelength. Table I shows the refractive index of these materials at various wavelengths, the refractive index for the perfect antireflection coating and the residual reflectance expected using ion-assisted quarter wave optical thick Al_2O_3 for the single layer AR. Al_2O_3 was chosen for the AR since it is the most common one used by manufacturers. GaSb is a material which we expect to see being used for devices active in the 2 mm – 5 mm spectral region. The refractive index is about 3.8 in those regions and a single layer AR would have a residual reflectance of about 0.9%

Table I

λ (nm)		N of InP [3]	√n	R (%)		N of GaAs [4]	√n	R (%)
810		~3.40	1.84	0.94		3.66	1.94	2.09
980		3.346	1.829	0.956		3.522	1.91	1.59
1310		3.205	1.789	0.626		3.423	1.887	1.25
1550		3.1665	1.78	0.54		3.423	1.884	1.26

Materials such as SiO, MgO and Y_2O_3 would result in lower residual reflection since they would be a better refractive index match. However these film materials probably would not be as durable. Al_2O_3 is usually the material of choice because it is very stable material and resists changes in structure or composition while being subjected to further device assembly steps.

Two layer AR

Lower reflectance can be achieved by going to two layers. The new material would have a higher refractive index so that the combination of the two materials would result in exactly zero reflectance. These thickness values are normally found by using a function in the thin film software that varies the thickness of each material to minimize a merit function (normally the actual value minus the target value over a wavelength range raised to some power). As an example, we have done this using TiO_2 as the additional material. Thus the design becomes GaAs (or InP)/Al_2O_3/ TiO_2 /air. The optical properties of the Al_2O_3 will be the same as for the single layer results shown in Table I. Deposition conditions for the TiO_2 will be those to achieve a moisture stable film (n=2.48 @ 560 nm). The thickness (in nanometers) of the layers needed to achieve 0% reflectance for InP and GaAs at the previously selected wavelengths is recorded in Table II. Although TiO_2 was chosen for this example, other high index materials would work equally well. However the film thickness would have to be varied due to the different optical properties.

Table II

λ (nm)		n of InP [3]	Al_2O_3 (nm)	TiO_2 (nm)		n of GaAs [4]	Al_2O_3 (nm)	TiO_2 (nm)
810		~3.40	69.2	23.5		3.66	57.1	31.3
980		3.346	79	32.6		3.522	77.3	33.5
1310		3.205	123.7	33.3		3.423	104.9	44.3
1550		3.165	132.8	47.3		3.423	124.1	52.3

Partial AR Coatings

There are some applications where a controlled level for the reflectance of the AR is desired, usually to optimise the resonance in the laser. This can be done by displacing the quarter wave optical thickness to a thinner or higher value if the reflectance desired is greater than that achieved with a single layer antireflection coating. As an example consider the desire to have a 4% reflecting surface for GaAs. The single layer centred AR would be 200.4 nm thick Al_2O_3 and result in a reflection of 1.25%. Using a thickness of 168 nm would displace the AR to a shorter wavelength resulting in a 4% reflectance at 1310 nm. Using a thickness of 232.9 nm would displace the AR to a longer wavelength resulting in a 4% reflectance at 1310 nm. See Figure 1 for a plot of the reflectance of these three films as a function of wavelength. The problem of using this method is that the manufacturing tolerance is reduced for the displaced coatings.

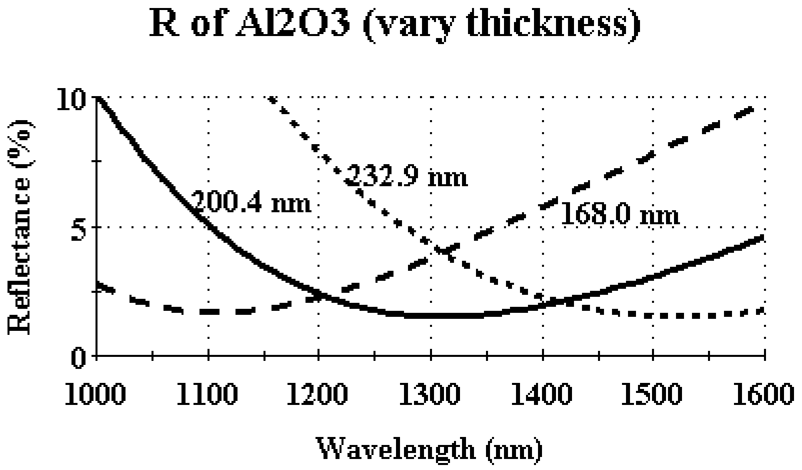


Figure 1. Reflectance vs. wavelength for different Al_2O_3 as indicated.

One can also displace the central wavelength of a two material two layer coating to get a higher reflectance than that achieved with the “perfect” AR coating. However, this also results in a reduced manufacturing tolerance for the displaced coating. The most logical optical way to do this is to design a symmetrical 3-layer coating consisting of two materials that results in the required reflectance. This structure is the easiest to adjust when doing the original development of the coating and will have a better manufacturing tolerance (see Figure 2).

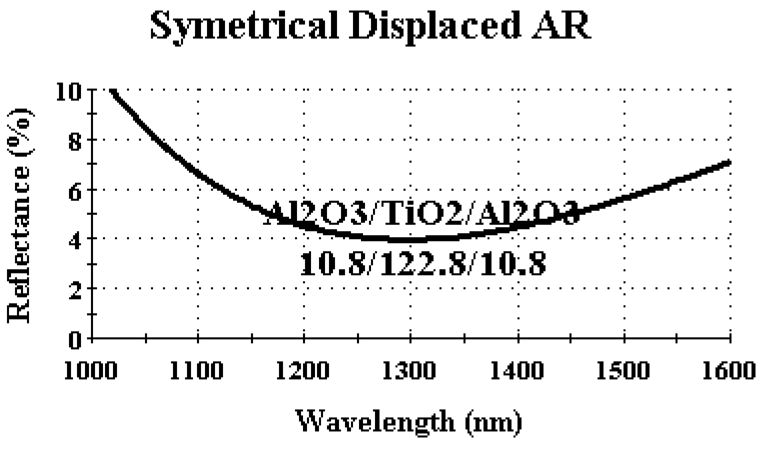


Figure 2. Reflectance vs. wavelength for symmetrical period as indicated (layer thickness is in nm).

High Reflector Mirrors

High reflector coatings are merely stacks of high and low index of materials with sufficient number of layers to give a high enough reflectance. The refractive index ratio of the two chosen materials will determine the number of layers needed. Fewer layers will be needed as the refractive index ratio becomes greater. For this reason many manufacturers chose to use a combination of silicon and aluminium oxide for the mirror stacks. Typically 6 to 8 layers will be sufficient. The problem with using this combination below 1 micron is that the silicon becomes absorbing and limits the ultimate reflectance to about 95% -96% at 810 nm. Using non-absorbing materials such as TiO_2/SiO_2 or TiO_2/Al_2O_3 can result in a reflectance as high as 99% or greater, depending on deposition conditions. The theoretical reflection of two coating combinations is compared in Figure 3. The higher index ratio Si/Al_2O_3 requires fewer layers (only 6) and has a much broader high reflection region than the lower index ratio TiO_2/Al_2O_3 (requiring 14 layers). The theoretical refractive index of silicon films is never achieved in standard E-beam evaporation where there are alternating layers of silicon and an oxide. This is due to the fact that residual oxygen left over from the oxide deposition combines with the silicon producing a lower index partially oxidized silicon film. Therefore the actual deposited stack will have slightly lower reflectance and not quite as broad a high reflection region. This is not a serious problem since in the worst an additional pair might be needed to bring the reflection up.

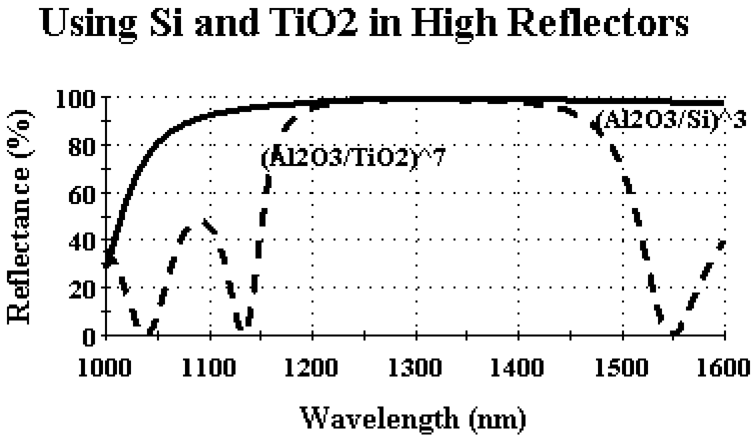


Figure 3. Comparison of high reflector stacks using Al_2O_3 as the low index material and Si or TiO_2 as the high index material.

Partial High Reflectors

There are situations where there is a need for some of the incident energy needs to be transmitted through the mirror (again to optimise the resonance in the laser). This is easy to do since the peak reflection is dependent on the number of layer pairs making up the mirror. For example, consider a mirror coating design of $(L\ H)^x$. The H stands for a QWOT (quarter wave optical thickness of a high index material and the L stands for a QWOT of a low index material. The lowercase x represents the number of times the LH pair is repeated in the mirror design. If x is 3 then there are a total of 6 layers in the design and if x is 5 there are 10 layers in the design. The following plot (Figure 4) shows the development of a mirror stack on GaAs as the x value is increased from 3 to 9 using TiO2 and Al2O3 as the coating materials. If the natural reflectance of a given number of pairs is what is needed, use it. Typically a desired reflectance and tolerance is not achieved with just QWOT layers. In that case one would use a design that gives a reflectance greater than the desired value and then tune the design in by symmetrically varying the thickness of the last three layers. As an example for this consider a design of $(L\ H)^x$ where x is 5 and the high and low index layers are TiO_2 and Al_2O_3 respectively.

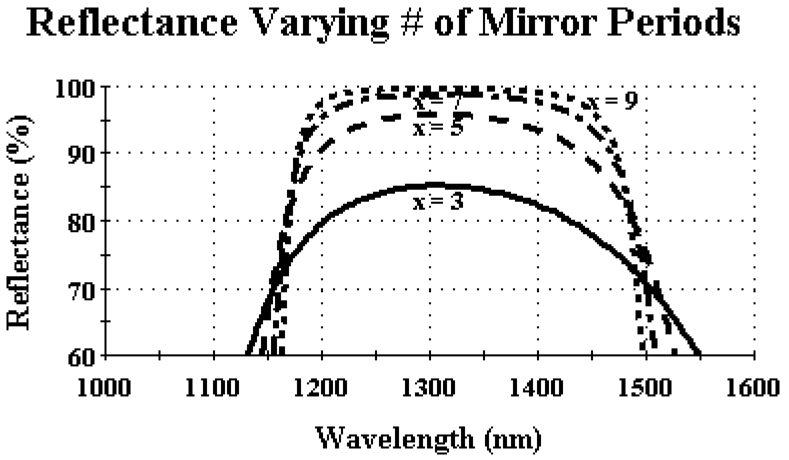


Figure 4. Reflectance plots of x = 3, 5, 7 and 9 layer pairs using TiO_2 for the high index material and Al_2O_3 as the low index material.

For example, if 80% is the desired reflectance, use the 3 pair (or 6 layer) design, vary the thickness of layers 4, 5 and 6 (while keeping layers 4 and 6 the same thickness) until you have the desired reflectance (as shown in Figure 5).

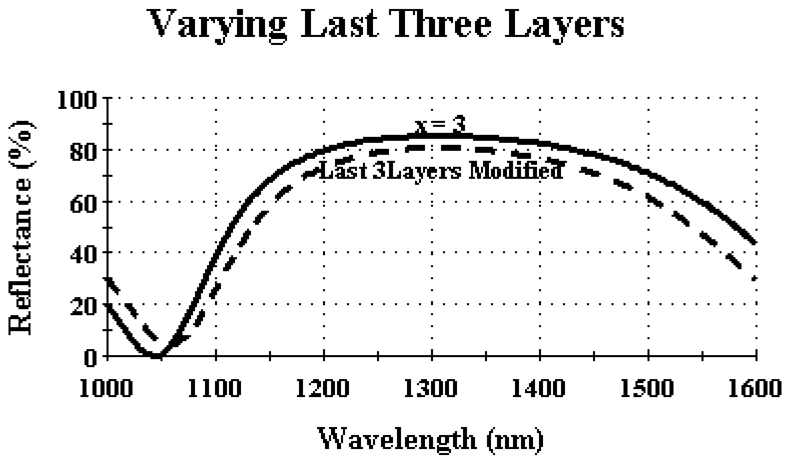
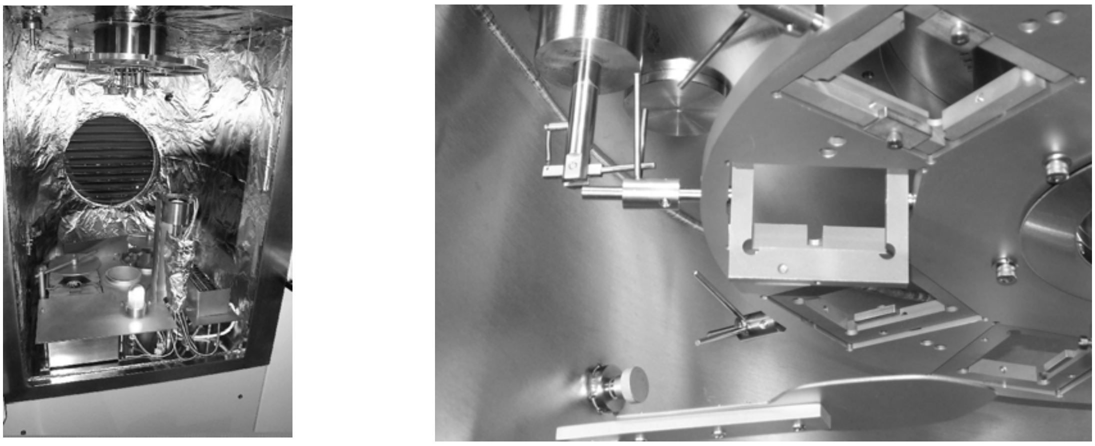


Figure 5. Comparing GaAs/LHLHLH design to a GaAs/LHL .648H 1.62L .648H design. The multiplier applies to the normal QWOT thickness.

It is important to note that all of the partial reflector designs have rounded tops and therefore the desired reflectance level is only achieved over a narrow wavelength band, requiring good thickness control when depositing these coatings. The lower the reflectance value the narrower the band. Whereas high reflectance levels are achievable over wider reflectance bands as the number of pairs are increased and the reflectance approaches 100%. Layer thickness control for coatings with very high reflectors are not nearly as critical as for AR coatings.

3. A Typical Flip Evaporator

Any high vacuum evaporation chamber can be used to do laser facet coatings. However, a typical size, configuration with specific components has evolved over time. Since laser facets are relatively small. They are usually coated in a long bar configuration and then sliced to size after coating. Also the chamber size needs to be only as big as is needed to accommodate the equipment inside the chamber and the tooling to hold the parts. Electron beam evaporation with an ion beam assist is the preferred deposition method. Typical tooling configuration is to have a single rotation fixture that will hold up to 8-three inch jigs which can be flipped to coat both sides in a single pump-down. The parts will be located on a relatively small area on the radius of the tool and will result fairly good deposition uniformity. However a mask is sometimes included in order to achieve the optimum uniformity. Adequate thickness control is normally achieved with a quartz crystal monitor. Further improvements in thickness control can be achieved by adding an optical monitor. Meeting these requirements usually results in a coating chamber with a twenty-six inch diameter and a height of about thirty-two inches. Larger chambers can be used but are not required. A typical system is shown in Figure 6.



a. b.

Figure 6. a) Internal view of a laser bar flip coater. b) View of flip tooling.

4. Results from a Flip Evaporator

All of the coating design types discussed in the design portion of this paper have been fabricated in coating equipment in our facility. Most of the coatings were done in equipment being built specifically for telecommunication manufacturers. Some of the coatings were done in our application laboratory as a development project. A few coatings have been done in our coating division as a toll coating service for customers who need production prior to getting there coating equipment built, installed and commissioned for production. Although we used GaAs laser facets in the design portion of this paper, all of the measured results were for either InP or GaAs facets. The differences in the designs for the two different facet materials is slight adjustments in film thickness needed to accommodate refractive index differences between the InP and the GaAs.

Evaluations of coatings done in our facility were done using a spectrophotometer to compare spectral results to design criteria. Evaluation of any actual devices was done by the customer buying equipment and the only feedback which we had for their evaluation was changes which might be desired or that they were satisfied with the device performance. We did not receive back any information on specific performance results. The usual substrate used for spectral evaluation was a wafer of the same (or similar) material as for the devices being fabricated. These wafers had one surface polished and the second surface etched. This configuration has a potential problem in that the quality of the back surface etch on samples supplied to us were not consistent. Accurate reflectance measurements on our spectrophotometer require that there should be no spectral reflectance coming back from the second surface of the witness samples. Witness samples for most optical work requires the reflectance samples have the back surface polished at a wedge so that any back surface reflectance is blocked out of the beam by an aperture. An alternative method is to roughen the back surface by grinding it to such a rough texture that all the light reflecting from the back surface is scattered form the beam. Initial measurements during our development work for AR coating resulted in inconsistencies that we could not understand. We felt that the second surface might be a problem and therefore scanned the second surface reflectance of InP wafers from several sources. The results showed significant variations as shown in Figure 7.

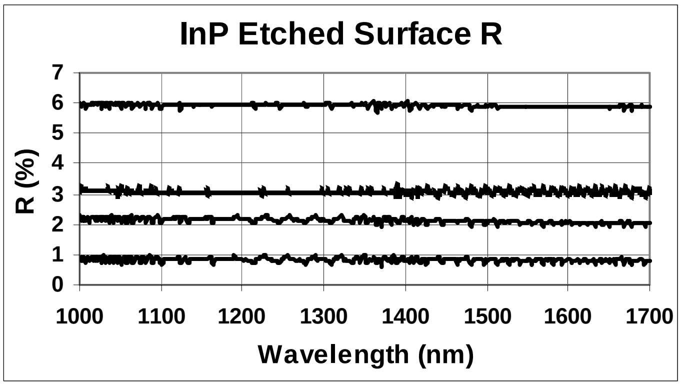
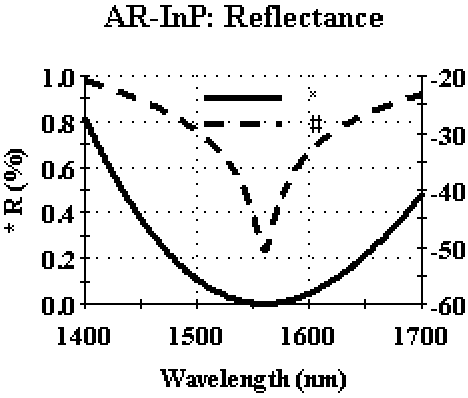


Figure 7. Spectrophotometer measured reflectance of etch surface of various InP wafers.

When the front polished surfaces of these wafers were coated with the same AR coating, the results were different. The measured reflectance was higher of the samples with the higher back surface reflectance than those with the lower reflectance. Furthermore, we found that by painting the back surface with a flat black paint (a technique often used in optical coating manufacturing), the reflectance could be reduced even more. Upon further investigation we found that the company which supplied the lower reflecting back surface samples had recognized this problem and were grinding the back surface of their wafers with a 1 micron grit powder to give them consistent results.

As a result of this study, our coating department requires customers to supply samples with a back surface reflectance of less than 2% (≤1% being preferred). We know that there is still an undefined residual reflectance but these samples our good enough to guarantee us to consistently confirm reflectance of ≤ 0.2%, and we typically get about 0.1%.

Figure 8 shows the computed "perfect" AR on InP at 1550 nm where the coating materials are TiO_2 and SiO_2.



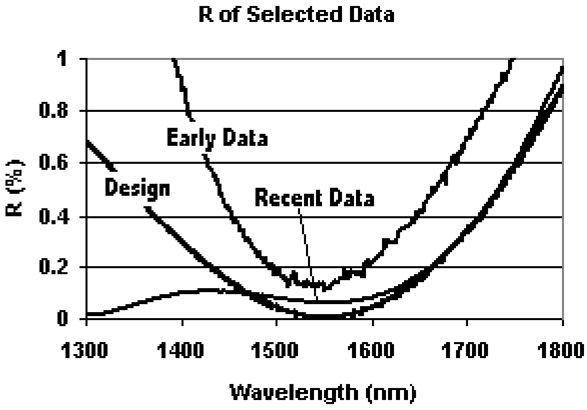


Figure 8. Close to the "perfect" AR on InP using TiO_2 and Al_2O_3 films.

Figure 9. A comparison of a 1550 nm AR to the original design deposited on InP. Also showing recent improved performance of dual band AR.

The measured spectral results of early depositions on InP are shown in figure 9. As can be seen the measured curve is not as low as the design due in part to random errors during deposition but mainly because there is residual reflectance from the back surface as discussed previously. In practice the design can be improved by doing a series of depositions and making slight variation in layer thickness to optimise empirically previous calibrations.

In the field of laser signal processing and telecommunications, the term Optical Return Loss (ORL) is used to describe the amount of light reflected at the end of a fiber or a laser bar facet. It is measured in decibels (dB) and is a logarithmic expression of the ratio of returned to incident light.

$\mathrm{ORL} = 10\log_{10}$ [Returned/Incident] (in dB)

It is desirable to reduce the return loss to the smallest possible value, and AR coatings are used extensively to accomplish this. The returned signal may not be exactly equal to the Fresnel loss at the coated interface: scattering, polish angle etc can cause a discrepancy, but if we ignore these effects it is simple to construct a table of reflectance and ORL values.

Table III

ORL (dB)	Equivalent Reflectance (%)	
-14.5	~3.5	Uncoated silica
-20	1.0	
-27	0.2	
-30	0.1	Typical high precision AR
-35	0.03	
-40	0.01	Ultra Low Loss AR
-45	0.003	
-50	0.001	

In our previous discussion, we stated that a typical high performance AR coating could have a residual reflectance of 0.1% – 0.2%, or –27 to –30dB. For telecommunications applications in recent years, an ORL of –30dB has been regarded by some as a barely acceptable minimum, with the majority of industry specifications requiring –35 to –40dB, some even more. These correspond to reflectance values an order of magnitude smaller than had, until recently, been the industry standard. To achieve such low reflectance values the coating process must be capable of extremely precise control of both film thickness and film index. The requirements have forced us to improve not only our manufacturing capability but also our measurement technology to the point where we can consistently produce such ultra low loss coatings and prove that they meet specification.

Figure 9 shows the measured reflectance spectrum of a dual band low loss AR coating. Fibers with this coating were measured with ORL values of –38dB at the primary wavelength (1310nm) and –32dB at the secondary wavelength (1550nm). These are quite consistent with the measured reflectance values of 0.016% and 0.06% respectively.

High reflector mirrors are less difficult to make. The reflectance bands are quite broad and they are much less susceptible to random errors in film thickness. Early work in our facility was for a customer who required Si/Al_2O_3 stacks for the high reflector on InP and the wavelengths of interest was 980 nm. Initial theoretical design performance and actual performance for an eight-layer design InP/LHLHLHLH is shown in figure 10. The optical properties of the Al_2O_3 were measured. The optical properties of the Si used were those supplied with the Essential Macleod software for Si (FILM) since we had no way for us to measure the properties of a strongly absorbing film. The film was actually deposited on a glass substrate since at the time we did not have InP wafers available. Theoretical calculations for the same stack on InP and glass showed little difference in the high reflectance regions. Therefore the difference shown here are the fact that the silicon film properties used in the theoretical model are not accurate. The center of the designed coating is longer than the center of the actual deposited coating. This is due to the fact that the initial single layer coatings are always close but not as close as desired. The calibrations can be adjusted for future coatings so that there is a better correlation.

There is a major variation from the peak reflectance values due to the actual and assumed optical properties of the silicon due to the fact that we had no reliable way to determine the actual optical properties of the silicon in the region where it was highly absorbing (below 1000 nm). An alternative mirror design would be to use TiO2 in place of the silicon. TiO2 is non-absorbing in this spectral region. However the refractive index is lower and therefore more layers are required. A comparison of a 12-layer design for TiO_2/Al_2O_3 (LHLHLHLHLHLH) and the coating deposited on a GaAs wafer is shown in figure 11.

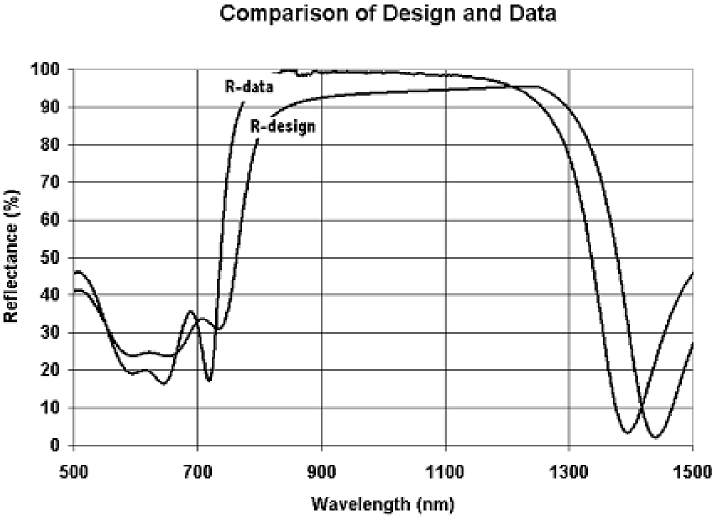


Figure 10. A comparison of a theoretical (R-calc.) LHLHLHLH Al_2O_3/Si reflector on glass and the first deposited stack on glass substrates.

Designs of either of these material combinations can easily be shifted out to 1310 nm or 1550 nm. Out at the longer wavelengths, the comparison between design and actual results for the Si/Al_2O_3 combinations are closer since we can get better optical properties for the silicon. However, silicon is a highly reactive material therefore it is critical that the deposition process is not started until the vacuum level is very low (typically $2x10^{-6}$ Torr) and that the amount of gas entering the chamber either through leaks or deliberate backfills are kept low so as to provide little or no oxygen for the silicon to combine with. This will result in silicon films with higher refractive index and mirror stacks with maximum width.

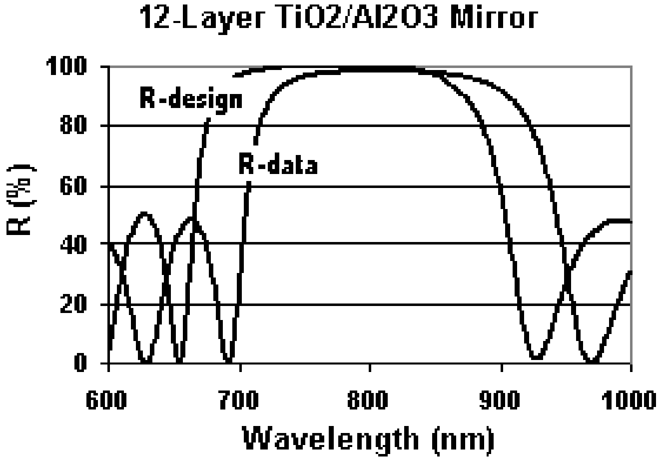


Figure 11. A comparison of a theoretical (R-design) LHLHLHLHLHLH Al_2O_3/TiO_2 reflector on GaAs and the first deposited stack on a GaAs wafer.

We had previously discussed partial reflectors where the coating design had the last three layers with thickness varied symmetrically so that the partial reflectance value equalled a required value. We have never made this coating although it is the preferred design method to do so. We have used an alternative technique for one customer who desired the coating to have a peak reflectance of 90% ± 2% on InP at 1550 nm. The materials of choice were silicon and Al_2O_3. A four-layer design LHLH has a reflectance of 95% and the 5-layer design of LHLHL would be about 87%. Once the first 4 layers have been deposited the peak reflectance value will start shifting down and to a longer wavelength as the 5th lower index layer is deposited. At some thickness for the 5th layer the peak wavelength will reach a maximum value and start shifting back while the peak reflectance value continues to decrease to the minimum value for the final thickness of the L layer. At some intermediate thickness value for the L layer the reflectance will be the required value. An example of this is shown in figure 12.

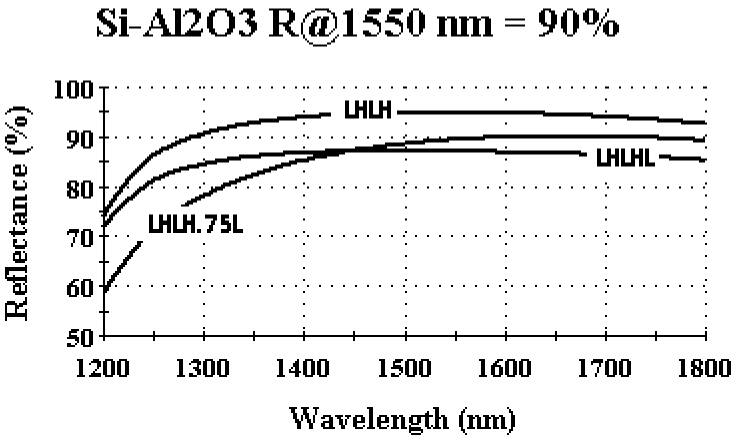


Figure 12. Plots showings theoretical technique for designing partial reflector with only outer layer thickness being varied.

In order to actually make this design the desired central peak wavelength must be divided by the central wavelength peak of the altered design and this scaling factor applied to the thickness of all the layers during deposition. When this is done the results of the first run done for this project are shown in figure 13. Again the final results are not exactly as would be expected, however, in this case they are within specification. The actual deposition results can be improved by making the outer layer slightly thicker will both move it on wavelength and increase the reflectance slightly. If desired, the layer ratios can also be altered slightly to further improve the results.

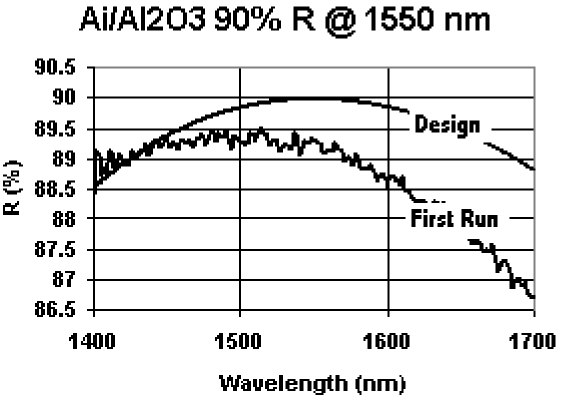


Figure 13. Comparison of 90% reflector design on InP and initial results.

CONCLUSIONS

In this paper we have shown a variety of designs and thin film material combinations for antireflection coatings and high reflectors for laser bar facets. We have also discussed some of the problems which optical coating manufacturers will have in measuring the performance of antireflection coatings on wafers that are normally supplied or used as reference samples. And finally we have shown examples of coatings made in various equipment in our coating facility and compared them to the original designs.

REFERENCES

1) D. E. Morton, “Characterizing Optical Thin Films (I)”, Vacuum Technology & Coating, September 2001, pp.24-31.

2) D. E. Morton, “Characterizing Optical Thin Films (II)”, Vacuum Technology & Coating, November 2001, pp.42-48.

3) P. Klocek ed., “Handbook of Infrared Optical Materials”, Marcel Dekker, Inc. New York, (1991) p 275.

4) Extracted from measured spectral data.