LENS TREATMENTS

PART 2: ANTI-REFLECTION (OPTICAL THEORY)

Peter Wilkinson PhD BSc(eng) CEng MIMechE is recognised as the UK's leading authority on spectacle lens surface treatments. He has extensive practical experience in lens manufacture particularly in the field of tinting, anti-reflection and anti-abrasion coating and holds senior positions in both the BSI and international standards organisations. After obtaining a PhD in engineering, and working initially at Rolls Royce, Dr Wilkinson was R&D manager at UK Optical, developed hard coating at American Optical and was then technical director at Cambridge Optical. He helped to develop Applied Vision's small AR coating process and has patented ideas for progressive lens design and for rapid acting photochromics. He now works as a consultant in ophthalmic optics particularly related to the manufacturing and quality of lens coatings. This series of articles was developed from a training course that he still teaches regularly for the Worshipful Company of Spectacle Makers

This paper reviews the relationship between refractive index and reflection, the wave interference effect and why it is significant. It also explains the necessity for quartz crystal control during AR coating, and the advantages of broadband coating.

Material	Refractive Index	Reflectance R_1	Reflectance R_T	Transmittance T
CR39	1.498	4.0%	7.6 %	92.4 %
Crown glass	1.523	4.3%	8.2 %	91.8 %
Mid-index	1.6	5.3%	10.1 %	89.9 %
High-index	1.7	6.7%	12.6 %	87.4 %
High-index	1.8	8.2%	15.1 %	84.9 %
Diamond	2.417	17.2%	29.3 %	70.7 %

▲ Table 1

What is the normal reflection of an optical material?

Although normally thought of as being a measure of how much light bends when entering an optical material; refractive index (written as n), is actually defined as the ratio of the speed of light in a vacuum, divided by the speed of light in the optical material. The refractive index of air is almost the same as in a vacuum so that $n_{air} = 1$. The strength of the reflection at an optical boundary (R_1) depends on the difference in refractive indices of the materials either side of the boundary (n and n'). If effects of angle of incidence, polarisation etc are ignored, then the reflection factor is given by:

$$R_1 = \frac{(n-n')^2}{(n+n')^2} \text{ but if } n' = 1 \text{ then } R_1 = \frac{(n-1)^2}{(n+1)^2}$$

This formula only gives the reflection at one surface, and if there is no internal absorption (ie no tint) then the reflection at the other surface must also be considered. The value of the total reflection R_T (for low values of reflection) is approximately double the reflection from one surface, or more exactly is given by:

$$R_T = \frac{2R_1}{(1+R_1)}$$

Ignoring any absorption, the transmission value is obviously 100% less the total reflection%. Values of refractive index (n), single surface reflection (R_1), total reflection (R_T) and transmission (T) for common optical materials are given in **Table 1**.

How are anti-reflection coatings created?

Anti-reflection coatings are possible because light travels as a wave and makes use of what is called the destructive interference technique. If the coating is a quarter of a wavelength thick, then the reflections from the front and the back of a coating layer will be out of phase with each other, therefore they will cancel each other out and there will be no visible reflection. This is illustrated by **Diagram 1** on page 4.

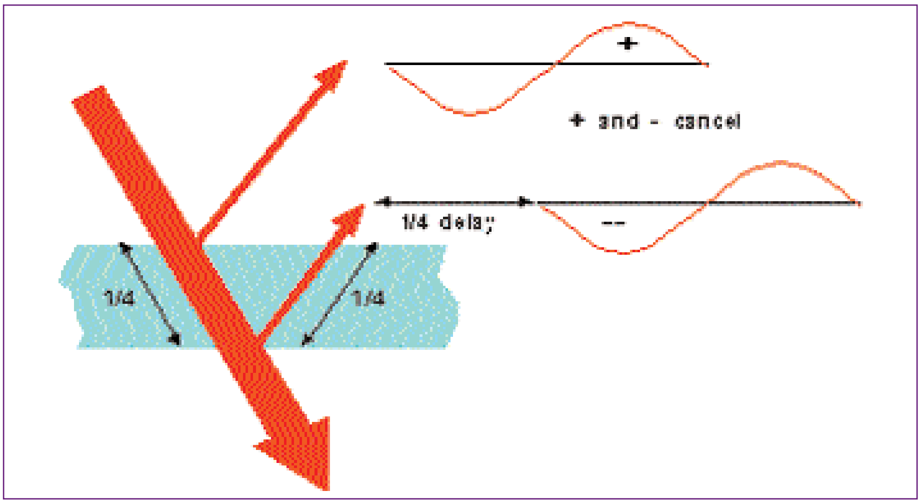
Not only must the two waves be exactly out of phase with each other, but they must also be of equal (and opposite) strengths. This is achieved by controlling the refractive index of the coating material. Where light travels from air (n_{air}) through a coating (n_c) into a material (n_m) then the reflection at the air-coating boundary must have the same strength as the reflection at the coating-material boundary.

Hence

$$\frac{(n_c-n_{air})^2}{(n_c+n_{air})^2} = \frac{(n_m-n_c)^2}{(n_m+n_c)^2}$$

This is satisfied, if the refractive index of the coating layer n_c is equal to the square root of the refractive index of the lens material n_m. (Note that $n_{air} = 1$)

If both the thickness and refractive index of the coating layer are chosen correctly, then there is no reflection at



▲ Diagram 1: the 1/4 wavelength interference effect (schematic only)

the surface. Also, because there is no reflected energy (and energy must go somewhere) then the light that would have been lost by reflection is actually added to the energy transmitted by the lens thus achieving 100% transmission.

However, this only works at one wavelength of light, as explained in the following paragraphs.

What is the significance of the visible spectrum of wavelengths of light?

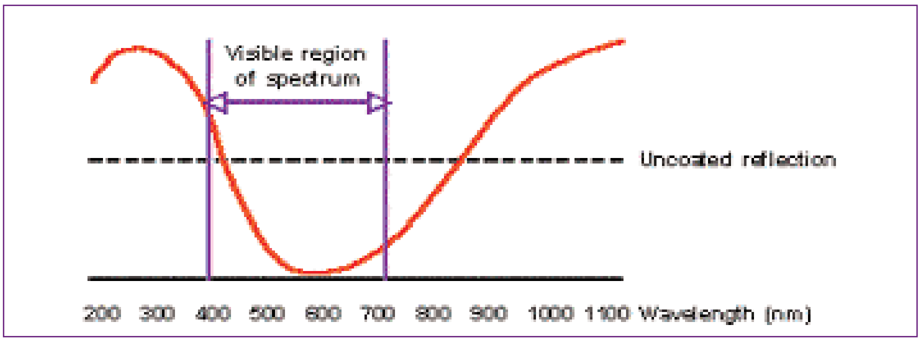
Destructive interference can only work properly at one 'design' wavelength. At other wavelengths, the quarter wave criteria is not satisfied exactly, or in the case when the light has half the 'design' wavelength, constructive addition occurs instead of destructive interference and the reflection is doubled. Because visible light covers wavelengths from about 400nm to about 700nm a variety of reflection strengths occur for different colours of light. **Diagram 2** shows the case where the design point is in the middle of the spectrum (at about 550nm) and therefore the double reflection points would occur at 275nm (and also at 1100nm). Coatings of this type are sometimes referred to as 'Vee' coatings because of the shape of the reflection curve.

Single layer AR coatings can therefore produce very low reflections at the design point but higher reflections at either end of the spectrum. Hence to appreciate how effective a single layer AR coating will be, you need to know where the design point wavelength is. It must also be appreciated that if the square root refractive index criteria is not satisfied at the design point then the minimum reflection will not be reduced to zero, but to some intermediate value.

Why are multilayers needed?

The principles described above (for a single layer AR), give low reflections at one wavelength, but residual colour from the ends of the spectrum remain. To achieve low reflection over the whole of the visible range, multilayers of different index materials are required. These are called MAR (multilayer AR), SAR (Super AR), or Broad-band coatings. These broadband coatings are often of very complex structure, with many layers of different index materials, but a simple explanation of how they work is given below. Remember that the refractive index of materials used should ideally have square root relationships to each other. One material easily available for coating is silicon oxide (SiO_2) which has an index of 1.46 and hence a material with an index of 2.13 is also required (because 1.46 = square root of 2.13). Other available materials are zirconium and titanium oxides, that have refractive indices of 2.0 and 2.3 (close to the ideal value of 2.13). This means that pairs of layers can be created having the necessary square root relationship. **Diagram 3** illustrates how two 'thicker' layers (with a reflection minimum in the centre of the visible spectrum) can be combined with a pair of 'thinner layers' having minima at either end of the visible spectrum to create a broad region of low reflection.

▼ Diagram 2: Reflection of a single layer coating



Does a hardcoat have an optical effect on an AR coating?

As explained above, any layers which have different refractive indices can react optically with each other to create different reflections, and these reflections will vary with wavelength. Hence a hardcoat will optically interfere with an AR coating (and also with the base lens material if the refractive index of the hardcoat has not been perfectly index matched). This means that it is important for any AR coating company to know the index of the underlying hardcoat if it is to prevent variation in reflection colours from lens to lens and even across the surface of a lens if the hardcoat thickness varies. Wherever possible the refractive index of a hardcoat should exactly match the index of the base lens.

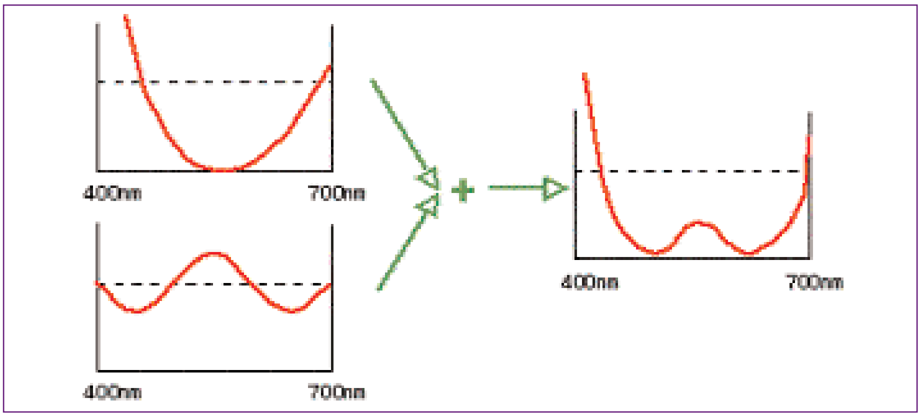
What factors are important in choosing the reflection colour of an AR coating?

Although it is possible to create different reflection colours, the most common is green (as illustrated in **Diagram 3**). Different manufacturers choose slightly different versions of green, ranging from a blue-green to a yellow emerald-green and some choose higher or lower values of reflection (of which more later), but very few offer other colours.

One of the main considerations is the manufacturing problems associated with obtaining consistency of reflection colour. Accuracy of control of both the coating layer refractive index and particularly its thickness is enormously more important for multi-layer than single layer coatings. Early single layer coatings were produced by simply timing how long the layer was being evaporated, but evaporated multilayers require such precise timing that a quartz crystal monitor is normally used. The minute vibrations of quartz crystals can be measured electronically (as in a modern wristwatch) and as the coating builds up in thickness, the quartz crystal becomes heavier and the vibration frequency is changed. From this the electronic monitor can deduce both the coating thickness and also the rate of deposition. Through a feed-back loop the logic system can control both the thickness and packing density of the coating. The packing density is important as this can affect the refractive index of the coating layer and other parameters. So critical is this timing that quartz crystals are normally only used once.

Excluding the obvious cosmetic appearance factors, other reasons for choosing reflection colour are optical. If a surface strongly reflects blue, then the light going into the lens will contain less blue. On the principle of complementary colours, the light absorbed into the lens will therefore be more yellow than normal. (Conversely, with a strong yellow reflection there will be blue absorption.) As with everything there are exceptions

Continued overleaf



▲ Diagram 3: Combination of two sets of layer pairs to create a broadband

to all rules and a blue reflective coating can enhance colour contrast for driving and so on.

What is the optimum reflection per cent ?

If the eye was equally sensitive to all colours and AR coatings simply reduced the amount of reflection equally for all wavelengths then a paler white reflection would be produced and the transmission % plus reflection % plus absorption per cent would total 100%. However, because the eye is not equally sensitive to all wavelengths, and because spectral reflectance varies through the spectrum, some form of averaging is required in order to be able to give a simple number. To prevent confusing marketing claims, a new International Standard has just been prepared that requires coating manufacturers to provide on request two values. One is the mean reflectance (just a simple average over the visible range) and the other is the luminous reflectance (which takes account of the relative sensitivity of the eye to different colours). **Diagram 4** gives examples of two coatings, a Vee coating and a broadband coating. They both have similar luminous (spectrally weighted) reflectance values but the mean (simple average) reflectance value of the Vee coating is four times greater than for the broadband coating. The relevant standard is listed at the end of the article.

However, a low reflection (and high transmission) is not necessarily the best coating for general use. The lower the residual reflection, the more difficult it is to keep a lens looking clean. It is not that the lens is actually any dirtier, just that it appears to be. It is worth pointing out that in Japan, where a very high proportion of people wear anti-reflection coatings, the industry normally provides a slightly higher reflection value than in Europe. The high proportion of myopes in Japan is of course also a factor because they tend to wear their spectacles continuously, and lenses for myopes have flatter front lens curves for which reflections are more obvious. When dispensing AR coatings it is important to consider the compromise between a lower reflection and ease of cleaning. For instance, a television presenter may want the absolute minimum reflection, but a manual worker may wish to have a coating where dirt is not so obvious. The residual colour of the coating also should be considered and related to any effect it might have on transmission colour as discussed earlier.

The next article in this series will discuss the practical aspects of AR coatings including how they are applied, hydrophobic layers and durability. With the number of lenses being AR coated in the UK still lagging behind that in Europe and Japan, we should ask ourselves, is it ethical to offer the inferior vision of an uncoated lens to spectacle wearers, when an easy solution to superior vision is available?

References

● ISO Standard 8980-4 'Ophthalmic Optics - Uncut finished spectacles - Part 4: Specifications and test methods for anti-reflection coatings'. This standard is available through the BSI under reference BS EN ISO 8980-4:2000 BS2738-10:2000.

A list of other references and further reading will be published at the end of the final article in the series. ■

▼ Diagram 4: Mean and spectral weighting