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Achieving the impossible? Holograms written by light from two separate lasers

Robert W Eason

Interference effects are easily observed using lasers. Their good coherence properties, high intensity and directionality make them ideal for laboratory demonstrations such as Young's slits. What happens if you attempt interference between two *separate* lasers, however? A static interference pattern is most improbable, but there are ways that this can occur, using photorefractive crystalline materials.

Almost everyone must have noticed the colourful patterns produced by a patch of oil spilt onto a wet road surface, and wondered about their origin. The rings of colour, rather like a rainbow pattern, are produced by interference between light reflected from the top surface of the air/film boundary and the bottom film/water interface. The reason why they can be easily seen even in white light is that firstly the film is very thin, sometimes of the order of only a few molecular layers, and secondly that the two interfering light waves are *coherent* with each other. This idea of coherence is fundamental to the whole concept of interference, and is discussed in most optics courses at college and university level.

One of the most easily understood experiments that demonstrates interference is that of Young's slits, which is usually performed with light waves, but can equally well show the wave-like behaviour of particles such as electrons. The key to observing interference fringes in this experiment is to produce two waves that will be *mutually coherent*. It would be quite useless to attempt to observe static interference fringes if two separate light sources were used to illuminate the two slits involved. As can be seen from figure 1, the arrangement uses one light source, which is effectively split to provide two equal components that will subsequently interfere on the screen. It is this property, that every source is coherent with itself, that forms the basis for almost all interferometers in use today. The interference pattern produced is a direct result of a spatial overlap between one portion of a wavefront and a second similar portion, perhaps delayed slightly in time through travelling to the observing screen via a different optical path.

The first observation of these interference effects was reported by Thomas Young in 1802, and represented a triumph for the wave theory of light. Using the newly named 'law of interference' he successfully measured the wavelengths of visible light, establishing the spectral range to fall between 0.7 μm for red light and 0.4 μm for blue light. Despite this tremendous achievement, which finally set optics on a sound physical footing, there were many scientists who objected to his manner, and criticized him heavily for his denunciation of the earlier ideas of Newton.

Robert Eason is a senior lecturer in the Department of Physics and in the Optoelectronics Research Centre at Southampton University. His research interests span nonlinear optics, dynamic holography, optical waveguides and devices, integrated optics, and anything optical. Before Southampton, he was at Rutherford Appleton Laboratory, and then a lecturer at Essex University.

Lasers as coherent light sources

Today, with the widespread use of lasers, we no longer have to resort to white light illumination for interferometric measuring systems. Lasers are much purer sources of light, having a much reduced spread of wavelengths than the light emitted from an ordinary light bulb, or even a gas discharge lamp, such as a sodium or mercury source. In fact a simple relationship can be used to determine the coherence length, L_c, of a light source which has a certain spread of frequencies, or optical bandwidth, $\Delta\nu$. The coherence length is a measure of the difference in path length that is allowed between the two beams such that interference will still occur and fringes be observable on

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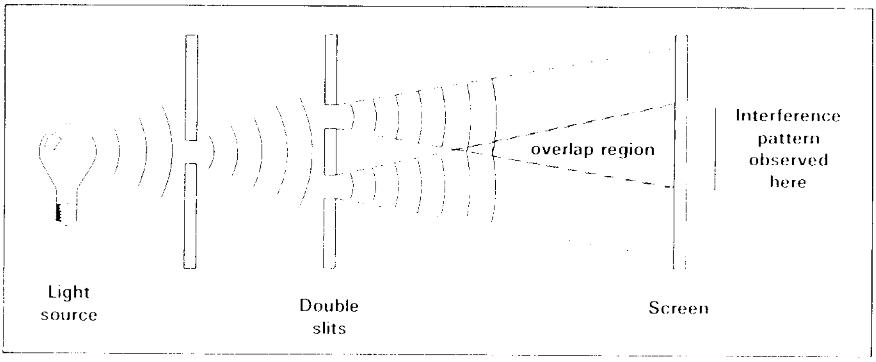


Figure 1. Young's slits interference experiment.

the screen. This length is expressed as

$$L_c = c/\Delta\nu \qquad (1)$$

where c is the speed of light. Therefore, for a white light source with a wavelength spanning the entire visible spectrum, the coherence length is only of the order of 1 μm, so observing interference between two white light sources is often tricky. If the two light paths differ by more than this value, then the interference pattern becomes progressively weaker as the mismatch in path length grows. For lasers, however, the situation is different. Most lasers, such as the common He Ne laser used in many laboratories, have a much narrower bandwidth: their coherence length is roughly 30 cm, so two overlapping beams will still produce interference patterns that are readily visible after this difference in path length.

Young's slits revisited

So, let us return to the Young's slits arrangement, but modernize it somewhat by using a laser source rather than alternative light sources available two centuries previously. In fact let us cheat and use two *separate* lasers, one to illuminate each slit. What happens now, to the interference pattern? After some thought, it should become clear that the pattern of light and dark fringes observed before with the single laser source will no longer be visible. The reason is that the two separate lasers are not in phase with each other: there is no coherence relationship between two separate lasers, even if they are both He Ne lasers, operating at the same nominal wavelength. In fact there will be interference occurring between the two light fields that simultaneously overlap on the observation screen, but any fringe pattern that occurs will be moving around at the optical frequency of the light involved. As your eye, or even the fastest detector available, cannot resolve such fast movements, we effectively see no interference pattern, and therefore only an averaged light intensity over the screen.

Interference and holography

Holography works on the same principle of interference. To record a hologram we require a light source that has a sufficiently long coherence length for two beams to travel different optical paths and subsequently interfere on a photographic plate. As shown in figure 2, one beam, called the reference beam, is incident on the plate directly, while the second beam, called the object beam, overlaps on the plate after being reflected from an object, such as a model or other suitably shiny surface. The clever thing about holography though is that the photographic plate records an interference pattern rather than a straightfoward image, and encoded in this pattern is all the information that is required to reconstruct a perfect three-dimensional replica image of the original object. It may take an exposure of several seconds, or even minutes, to record this spatially complicated, extremely detailed interference pattern, during which time any movement of the object, plate or optics involved will destroy the fine detail required to faithfully replay the hologram to view the original object. For this reason, professional holographers go to enormous lengths to ensure stability of all their equipment, and even worry about air turbulence during their long exposures.

However, the requirement for holography is the same as that for interference. The two beams of light, almost always laser light because of its superior properties, must be mutually coherent. It may therefore come as a surprise to learn that it is quite possible to record holograms between two laser sources that are not only *mutually incoherent* but can even be of different wavelengths. How come? The answer is to use not a holographic plate

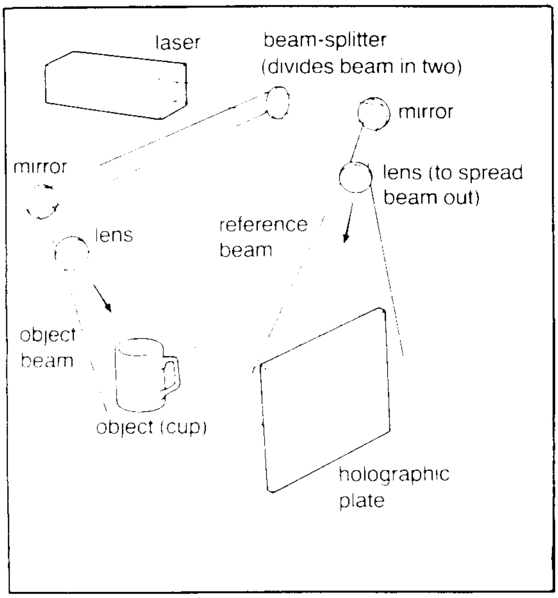


Figure 2. Procedure for recording a hologram.

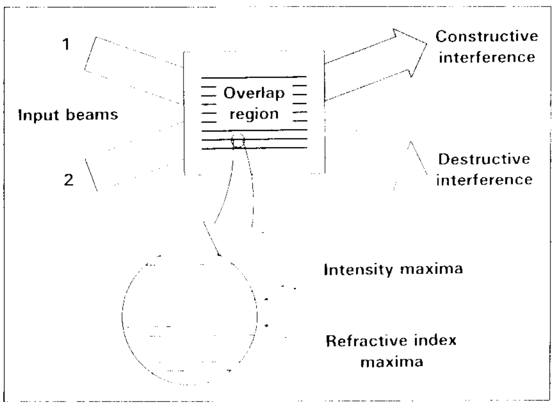
but a crystal of a material that can store holograms through small changes in the local refractive index where the light intensity is higher than average, within the interference pattern. These crystals are called photorefractives, and the interference effects that occur between two separate lasers, of different wavelengths even, is termed *mutually incoherent beam coupling*. This surprising result was first observed seven years ago (Sternklar *et al* 1986), and since then a flurry of activity has surrounded this particular branch of nonlinear optics research.

Interference between mutually incoherent light beams

To explain how this can occur, we need briefly to discuss the mechanisms involved in photorefraction. Consider a spatially varying light intensity pattern, for example a fringe pattern produced by two-beam interference as in figure 1, that is incident on one of these crystals. The crystal responds to the varying distribution of high and low intensities within the inteference pattern by generating an exactly matching, spatially varying refractive index pattern. This pattern, or grating, can itself then diffract any optical beam that is incident on the crystal, and in fact, because the two incident beams that made this grating are still there, they themselves will be diffracted. The clever thing about these crystals, however, is that the matching refractive index grating is spatially identical to the light pattern that created it, apart from one very important factor: there is a spatial shift in the whole pattern by precisely one quarter of one grating period. With reference to figure 3, we can now see what happens. The spatial shift, together with a further shift caused by the diffraction process itself, means that in one direction the diffracted part of beam 1 and the straight-through component of beam 2 add constructively, just as beams with the right phase do in an interference experiment. On the other hand, the diffracted part of beam 2 and the straight-through component of beam 1 are not so fortunate, and in this case the combination of spatial shift and diffracted beam phase shift leads to destructive interference, so not much light comes out in this direction. This whole process is called two-beam coupling, and provides a self-generated holographic link, which has aroused much interest for automatically combining two or more laser beams.

There are some surprising consequences to this phenomenon. Firstly, unlike conventional holography, the holographic grating formed does not require any wet chemical developing procedure, and it is not a static process either. If you move one or both of the beams, then the grating moves too, and the crystal re-learns what it should do. Secondly, if both beams contain picture information, such as occurs from passing the light through a slide for example, then there is no mixing of the picture information between the two beams. The amplified beam in figure 3 does not contain any of the spatial information contained in the amplifying beam. Perhaps most surprising is that in practice you don't even need to use two beams. Very small amounts of light scattered within these crystals are sufficient to start this coupling process, so that once a laser beam is shone into a suitable photorefractive crystal, the coupling between scattered light and the main

Figure 3. Schematic diagram of two-beam coupling that occurs in photorefractive crystalline media.



beam grows rapidly, diverting the incident beam into a direction in which this two-beam coupling gain is largest. Looking at such a crystal is disconcerting, because the laser beam does not travel in a straight line. It is progressively bent by the succession of self-written holograms that are distributed throughout the crystal.

The final surprise comes about if not one, but two separate laser beams are incident on the crystal simultaneously. There are several geometries that are possible here, and the five most popular ones are shown schematically in figure 4. Their sometimes curious names were chosen by their inventors to describe the paths taken by the beams within the crystals, and also to show that even optical physicists have a sense of humour!

Mutually pumped couplers

This self-bending effect is shown quite convincingly in figure 5, where two mutually incoherent laser beams were directed simultaneously into a photorefractive crystal (Eason and Smout 1987). If we look at the schematic diagram in the lower part of figure 5, it is possible to see what is occurring. The first beam (1) undergoes this self-bending via an extremely large number of self-written holograms. It is true that, within this number, one unique hologram in this volume may exist that is exactly the correct one to send beam 1 into the direction of beam 2, to form a precisely counterpropagating beam of light for beam 2. An exactly similar argument applies the other way round for beam 2 self-bending into the direction of beam 1. The surprising fact, to me at least, is that this process does actually occur, leaving a single, admittedly complicated, hologram surviving in the crystal, which automatically self-routes each beam into the other's direction. Why this occurs is still under some discussion, but it is an example where hologram-sharing is beneficial to both beams. All non-overlapping holograms are erased and one survives. It's a case of winner-takes-all, or crystal altruism!

Once you have accepted this idea, the inquisitive amongst us must ask the question: 'what happens

Figure 5. Photograph of mutually incoherent coupling in a $5 \times 5 \times 5$ mm^3 crystal of $BaTiO_3$. Note how the two laser beams travel in curved paths rather than straight lines.

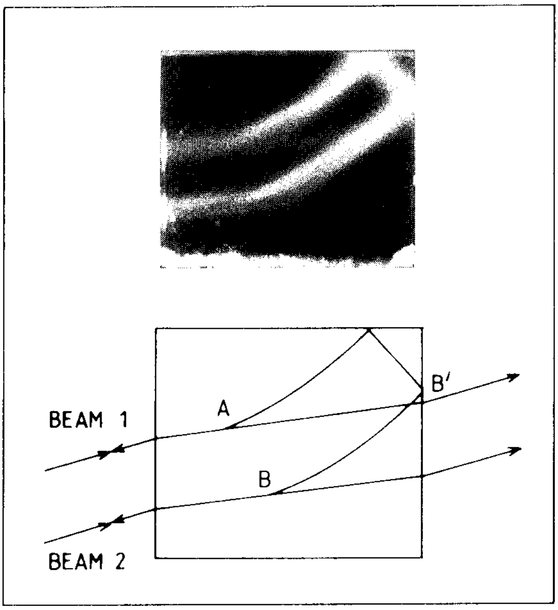
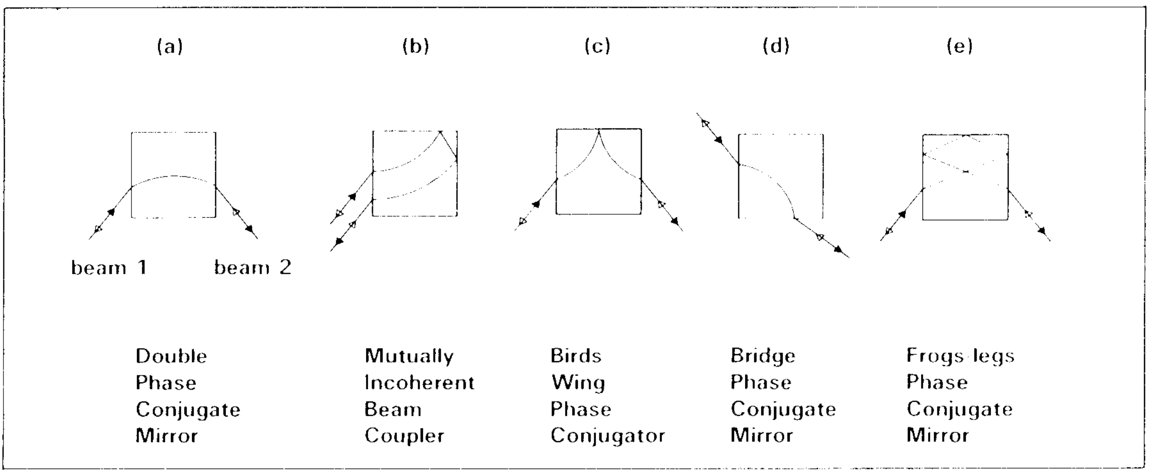


Figure 4. Various geometries for mutually incoherent beam coupling.



if the wavelengths of the two beams are not identical?' The same argument applies, surprisingly, and some of the configurations shown in figure 4 allow two separate lasers of different wavelength to share the same hologram. This time the directions of the generated beams will not follow the input beams exactly, so some directional tuning will occur. The result of this is that two lasers working initially at different wavelengths may self-lock to the same wavelength by a process of back-injection. That the process works at all is strange, I believe, but that it is tolerant to different wavelengths is remarkable. For the configuration of figure 4(*a*), the inventors have coupled together lasers working in the red and blue spectral regions, something unthinkable using conventional interferometric principles. In our own work we have chosen to investigate the near-infrared spectral region, where in addition to the coupling of different wavelengths, we also see that the diffraction efficiency can be so strong that more light comes back to one of the lasers than it sent into the crystal to start with! The crystal has made, by itself, a self-aligning, wavelength-tolerant, wavefront-correcting mirror with a reflectivity of >600% (Ross and Eason 1993).

Conclusions

In the two centuries that have passed since Young's wave theory first saw the light of day, there has been a constant momentum in optical research, towards communications, measurement and, more recently, laser science. Any suggestion that research and development in these areas will cease carries little weight amongst those engaged in the field of optics, where surprises such as this are extremely exciting, and it tempts us to look even harder for the next challenge. Hopefully, optics will not hide her secrets too well.

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