Alignment of Optical Systems Using Lasers: A Guide for the Uninitiated

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SPIE Spotlight Series

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Craig Olson, *Series Editor*
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Preface

I learned the basics of optical alignment initially from my PhD supervisor and the rest I acquired over 3 decades in optical laboratories. Seemingly little has changed for this process of knowledge acquisition even though the world of scientific publishing has vastly expanded and moved to an electronic format. There is a lot of information about what to do with optics, seemingly little about how to go about doing it. Hence I decided to record the thoughts and methods I use regarding optical alignment. This book is not intended to be rigorous in scientific detail, more a guide to point you in the right direction. Neither is this book a beginners guide to optics but assumes familiarity with light, its control and the basic components used. You ultimately learn optical alignment by doing it, but you can save a lot of time by starting out in the right direction.

1 Introduction

The alignment of optical systems is a skill. It is a skill that is often overlooked or assumed to be obvious. Maybe this arises from a view of "aligned" optical systems that is easily understood, inherently interpretable. Maybe it arises because optical experiments can be performed at school and are therefore assumed to be simple. But anyone who has spent time in an optics lab will know the frustration of spending hours, sometimes days, trying to effectively align an optical system, so where does this disparity between perception and reality come from? Perhaps, it is that undergraduate experience of optics experiments. I often explain to students that the difference between education and research is that as a student you embark on a known path where the experiment has been constructed; there is a method and an expected result. This is not the case with research where you need to decide upon an appropriate method, which may not work. There is not necessarily a defined endpoint. You may spend a considerable time pursuing one line of investigation, to then abandon it and try something different. With predefined experiments, you usually make use of optical rails to mount optical components and these are known to be compatible with each other. This significantly reduces the difficulties involved with alignment.

This Spotlight is aimed at someone new to the optics lab such as a new research student but not new to the ideas of optics, i.e., you understand that a lens focuses light. (It may seem strange to say this but I have met many people who did not actually know what to do with a lens or how it works.) This Spotlight provides the philosophy and rationale behind optical alignment. Aligning optical systems is a skill that is acquired through several years of constructing optical systems of various kinds, yet it is not something we tend to celebrate with lines on our CV. It is a skill that comes through patience and failure. If a student needs to understand an aspect of science, there are countless journal papers and text books to refer to. There is very little on learning to do optical alignment.[1] A useful source of information is to be found with the optical equipment manufacturers who often provide tutorials and primers on how to use items of optical equipment.[2–4] These are very useful and informative but do not give instruction on how to perform fundamental alignment procedures.

As a research student, you are presented with a clear optical table on which you have to produce an aligned system. You may have to choose which elements and which form of mounts you will need. You will assume that you know how to proceed and then you will find that it takes much longer than you expected, you change the setup often and then your supervisor will come in and change everything.

This Spotlight is intended to pass on some nuggets of knowledge about how to go about setting up an optical alignment using a laser and some tricks to use to make life easier. Hence there are other topics that are important to grasp, topics that may have been presented in lectures but not faced in reality—such as chromatic effects and collimation. It is not intended to be rigorously scientific in its approach but more as a companion on your optics journey.

1.1 A word about laser safety

You must make sure that you familiarize yourself with the laser usage and safety procedures in your laboratory. Every organization should have its own set of procedures and policies regarding working with lasers and risk management. A quick internet search will provide you examples and generalist sites, such as Wikipedia, give a good accessible overview[1] (see Ref. 5 for a more in-depth appreciation). It is not necessary to use bright lasers to achieve alignment; we are mostly interested in a lasers ability to travel in a straight line. I would strongly recommend that lasers are attenuated (using neutral density filters) and should be well below the level of 1 mW, ideally <100 μW, making them class 2. (This is ideal, it may not be possible depending on your laser and system.) Laser safety procedures will assess the nominal ocular hazard distance (NOHD) for the laser you are using. If it is deemed that you need to wear personal protective equipment, i.e., protective goggles, this will be a major hindrance because you will not be able to see the beam you are trying to use. Thus using a low-power laser with a short NOHD is ideal here.

1.2 Laboratory good practice

Never touch the optical surface of an optical element with bare fingers. Sweat and grease from your fingers will leave marks and can impact upon optical performance. Handle lenses and mirrors by their edges. In other cases, such as beam splitters, wear disposable gloves.

Do not leave unmounted lenses lying on a hard optical table. This can scratch the middle of the lens surface. Do not leave mirrors face down for the same reason. Return optical elements to their packaging or protective case.

Do not mix metric and imperial equipment together. You might be able to make an imperial thread fit in a metric hole, but you will almost certainly damage the thread within the hole and you may get components permanently attached. It is extremely frustrating to pick up a piece of mounting equipment to find it does not fit with all the other equipment you have put together.

Before embarking upon aligning a system, draw a schematic diagram of the system showing all the components you will need, their relative positions, and what their functions will be.

White business cards make excellent screens for viewing the beam at various points in the chain of optical elements.

2 How Alignment Can Go Wrong

Let us start with an example task. Your job is to take a laser, focus it though a pinhole then expand the beam and direct it with a mirror to a camera. It does

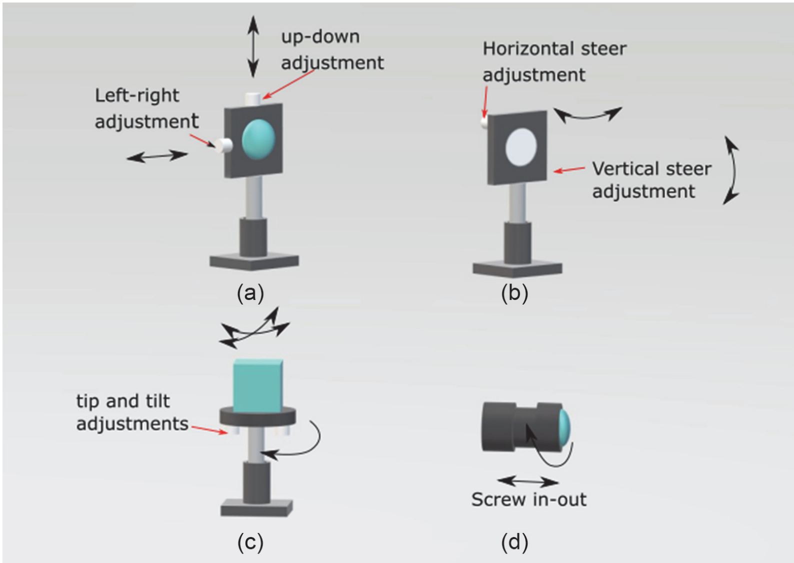

Figure 3 The basic adjustments found on typical mounts for optical elements. (a) Lateral adjustments for a lens, (b) angular adjustments for a mirror, (c) angular adjustment on a mounting table, and (d) lateral focus adjustment for a lens.

table upon which cube beamsplitters or prism is mounted, although in this case Fig. 3(c), rotation of the post in its holder is an important adjustment. The final adjustment is lateral displacement of a lens along the z direction to change focal position [Fig. 3(d)] in this case achieved by threaded tube mounts. There are other ways to achieve this such as placing the entire mount on a translating table, usually adjusted with a vernier drive. Often a lens in such a mounting will also need to be mounted with type (a) giving three adjustment directions.

3 Working with Lenses

Before getting stuck-in to the process of alignment, it is important to get a grasp of what optical components are actually doing. The fundamentals of optical theory are widely accessible in many textbooks and websites.[2,7–9] Here, I will relate only those things that are needed for a fundamental grasp of using lenses.

The focusing properties of lenses are most familiar in the form of the thin lens equation:[7]

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}, \tag{1}$$

where u is the distance from the object to the lens, v is the distance from the lens to the image, and f is the focal length of the lens. We are assuming here that this is a single lens that is “thin.” (Multielement lenses, such as one on a camera,

3.6 Chromatic aberration

The refractive index of a material is the ratio of the speed of light in vacuum to the speed in that material. It is this difference in speed that causes light to refract as it transitions into and out of the material. The refractive index is dependent upon the frequency. In the case of glass, water and other light transparent materials the refractive index increases with frequency, or as the wavelength decreases. Thus blue light experiences a higher refractive index than red light. We know from the well-known Snell's law that higher refractive indices result in larger angles of refraction, thus blue light entering the curved surface of a lens is refracted more than red light. The result of this is that blue light is focused closer to the lens than red light, which in imaging terms is an effect called chromatic aberration. The effects of chromatic aberration can be systematically reduced by combining two lenses (a positive and a negative lens which show opposite chromatic effects) made of materials of differing refractive index into a single combined lens known as a doublet lens. This will usually seek to focus the red and blue wavelength to near the same point with the green portion being separated a little. The difference between a singlet and doublet lens is shown in Fig. 8. Note that chromatic aberration is not removed, just reduced.

A little thought may prompt the question "Why do I need to worry about chromatic aberration if I am using a laser which is a single wavelength?" Well, if you are only using the laser then that is fair enough. But if you are using the laser to align a system that will be used with broadband light then chromatic aberration will be an issue. If you plan to use different lasers with different colors chromatic effects will be present. Chromatic aberration is mentioned in order that you can plan ahead based on the use of your optical system. If you know that you are going to be using multiple wavelengths then expect chromatic aberration and use doublet lenses accordingly, it will reduce problems in the long run. Also doublet lenses are often designed to reduce other aberrations such as coma and spherical aberration that can be present in singlet lenses, thus they can improve image quality, reducing focal spot sizes.

Imaging systems, such as cameras, are broadband and must account for chromatic aberrations to produce good quality images. They use compound lens systems to correct chromatic and other aberrations. Therefore, it can often be helpful to use a camera lens if you are wanting to produce an image or even just a good quality consistent focal position. Often small (C-mount) camera lenses can be obtained cheaply or second-hand film camera lenses can be useful—it is mounting them that will be the biggest problem!

4 Defining the Optical Axis

The laser is your friend when it comes to alignment. We all know that lasers travel in straight lines—so in the initial example alignment case we can use the laser to define where the elements should go, not the other way around. In a

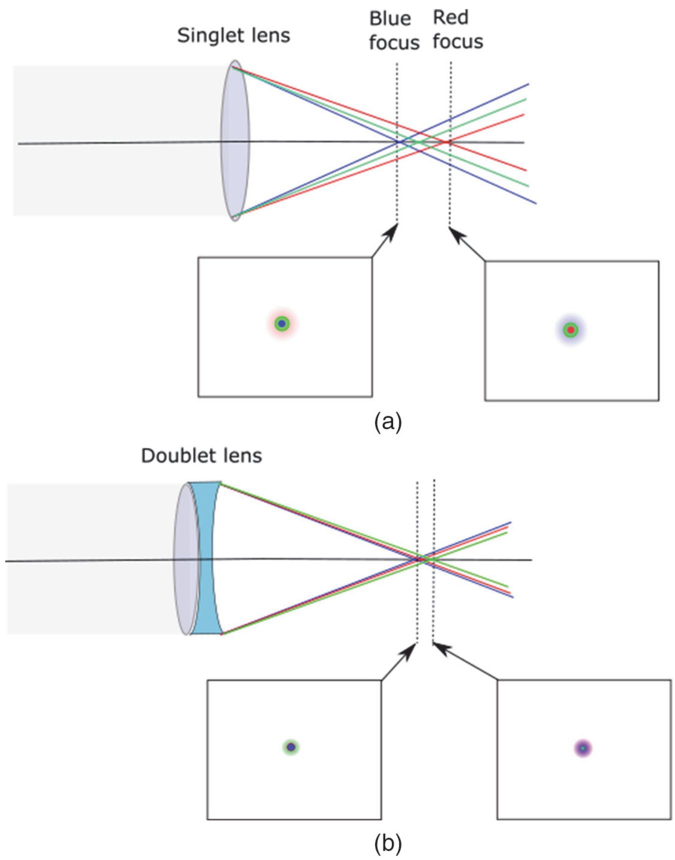

Figure 8 Different focal planes of red and blue light with a representation of focal spot size for red and blue at the respective focus. (a) A singlet lens and (b) a doublet lens with reduced aberration.

system like the poor example shown initially, all the problems arise from the laser pointing up slightly. So let us set out a procedure to align that system correctly.

- The first thing that should be done is to ensure that the laser travels in a horizontal plane. Once we have done this, we can "see" where the optical axis is. The preferred way to do this is using two adjustable apertures. We choose a height for the laser, then set the height of the apertures to be the same as the laser by placing them right next to the laser, seeing the laser pass through, and reducing the aperture size, progressively tweaking the height.
- Now separate the two apertures by say, 0.5 m or more and see if the laser passes through both apertures. Adjust the tilt of the laser—usually the height of the rear of the laser support. (You defined the front height to be the same as the apertures so do not change that!) Also twist the laser as

- Mirror M2 should be lined up as close as possible to be in line with the optic axis through apertures A1 and A2.
- Set the height of the center of M2 to match the aperture height. Now place M1 to direct a beam from the laser onto M2—this is where the change in height between laser and system is rectified.
- Next steer the beam using M2 to pass through the aperture A1. If you have done a good alignment by eye, the beam should appear somewhere near the aperture A2 (as shown in Fig. 9).
- At this point, your instinct will be to try and steer the beam through the second aperture and as you do this you will find the beam disappears as it does not pass through A1. This misalignment means we are not hitting the correct position on M2 to meet with the optical axis.
- The trick to correcting this is as follows.
  - Concentrating on one direction, say horizontal, use M1 to steer the beam spot on A2 *further away from the aperture*.
  - Now use a horizontal adjustment on M2 to bring the beam back toward the aperture. You should see the beam spot is closer than it was.
  - Keep repeating this until the beam spot is vertically aligned (correct horizontal position) with the aperture.
  - Now repeat the process for vertical adjustments of M1 and M2 until the beam passes through both apertures.
- We have now aligned the laser with the optical axis of the system and it is important that we lock down the mirrors to ensure the direction remains fixed. The apertures can be taken away (if you must) and the system between the apertures then aligned with the laser.

This dog leg arrangement proves useful in most situations when precise alignment is required—such as interferometers, fibers, and cavities—and is significantly easier than trying to align a laser by itself to an optical axis which would require getting the height, position, tip, and tilt angles of the whole laser to match an optical axis.

5 Focusing into a Fiber

Focusing a laser beam into a fiber presents a different kind of challenge and requires an extra level of patience. The task you face is to pass as much of the light through the fiber as possible. The core of an optical fiber can be around 10 μm in diameter for a single-mode fiber. Thus we must focus the laser to a size smaller than this and align the laser with the optical axis of the fiber.

We must therefore use a lens with a suitably short focal length to ensure the laser focal spot size is smaller than the core. We can get this approximately from

$$f = \frac{d\ x}{2.44\lambda}, \tag{10}$$

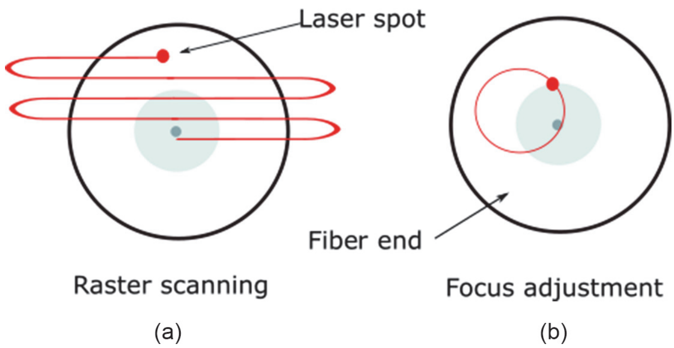

Figure 11 Actions for focusing into a fiber (a) raster scanning technique and (b) lack of concentricity causes focal spot to rotate with a screw focal adjustment.

- When the lens is moved it rotates the focused beam around the optical axis (see Fig. 11). Operate in whole turns so that the spot returns close to its initial position then tweak the position to optimize. Note that you will need to use the locking ring—release, adjust, and retighten the ring—each time because the act of releasing the locking ring relaxes the mount and moves the spot.
- Once the best position for whole turns is located fractional turns that home in on the best focus can be used.
- This may be adequate to focus into multimode fibers, but if you are using a single-mode fiber you will need much more precise control over the lens position using some form of translation stage with a micrometer control.
- Once you get close to the correct focus you should see the power increase significantly, but you will also see the sensitivity of the adjustments increase.

When using a visible laser, there are some visual clues as to what is happening (sadly more difficult with IR). When the laser strikes the end of the fiber, the fiber will light up along its length. This is light that is trapped in the cladding region. This at least tells you that you have found the end of the fiber! When you get close to correct focus, you can sometimes observe a brief dip in brightness of this light as a significant portion gets trapped in the core.

To repeat a useful tip, when you have found the best focus position, fix things in place! This means the mounts, the posts, and locking rings.

6 Aligning an Interferometer

6.1 The Michelson interferometer

Interferometers work by dividing light into two paths and then recombining these paths to produce interference. The interference intensity usually varies

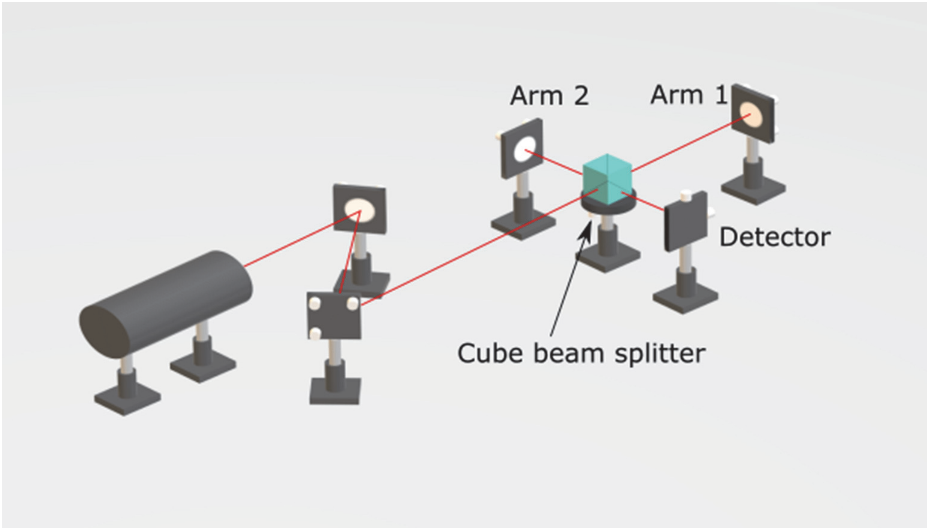

Figure 12 An example optical setup for a Michelson interferometer.

sinusoidally with path length difference between the two paths (usually referred to as arms). This sinusoidal variation can be seen either spatially as fringes, or temporally as a varying intensity level. When light from the two paths recombine, we are repeating our earlier task of overlapping two optical axes and we must do this to ensure interference. Let us start with the Michelson interferometer (see for example Ref. 7). Our task here is to use a beam splitter to divide an input laser beam and then use two mirrors to form the two arms of the interferometer and redirect the light back into the beam splitter, combining the light that exits in a third direction where it is detected by a detector, as shown in Fig. 12.

- Again start with the dog leg arrangement to introduce light into the interferometer and you should use apertures to define the height parallel to the optical table.
- Introduce the beam splitter, in this case a cube, and work with the beam that passes straight through (arm 1).
- Using a mirror reflect the light back toward the cube.
- Place a detector to catch the return beam that is reflected by the beam splitter cube.
- Repeat for arm 2, ensuring the beams from both arms meet at the detector by steering using the mirror in arm 2.
- As long as the beams from the two arms overlap on the detector, interference should be observable. This is made possible by two convenient facts that make this experiment suitable for undergraduates.
  - We can use a large area detector that can detect the whole laser beam.

    - Adjust M2 so that spots overlap
    - and as you close in you start to see interference fringes
    - The fringes should get larger and pass through less quickly as you get closer to the position of best alignment.
- The curvature of the fringe shows you the direction you should move the spots as you should be aiming for the center of a set of circular fringes. If you cannot see interference fringes then you have not actually overlapped the beams from the two interferometer arms (You have overlapped the spots at the position you are observing but not matched the beam directions through the interferometer). If the distant spots are overlapped, then observe the spots at the detector position and you will probably see that they are not coincident. The beams from each arm are not collinear and cannot interfere—they are in different spatial modes.[11] To correct this, we need to physically translate one of the mirrors so that the beams travel in the same direction as they exit. Keep checking the spots at the detector and then further away as you move the mirror a small amount. When they look like they overlap then fix the mirror down and repeat the alignment process by looking for interference fringes.

An extra layer of difficulty appears, if we introduce a lens before the interferometer to focus onto the detectors (this will improve the field of view of the system). The smaller spots that arise from focusing require a much more precise level of alignment to ensure that they overlap—it might sound obvious but with a large detector then both spots could be striking the detector area but if they are not overlapping there will be no interference. The spots are only small at the detector, when you move back some distance the spots are much larger, therefore dimmer and produce linear fringes.

As a final comment, it is worth noting that this interferometer has two output ports which means that using a single-port wastes half of the light/signal. Detectors can be placed at both ports to collect all the light and if the detector signals are subtracted (a balanced detector) the common noise is reduced and the signal is doubled because the light from each exit port is in antiphase—I leave this as an exercise for the reader!

7 Aligning with Lenses

Aligning and defining the optical axis is best done with "passive" components such as flat mirrors. (Note that curved mirrors are not passive as they focus light.) In many cases, we would want to include lenses in our system to provide a focal point of high intensity or a position of efficient light collection. We can use the same principles as before but be aware of some differences. An off-axis beam through a lens will be steered at an angle, thus it is important to centralize the beam. This is done at first by eye and then more precisely using reflections. Many lenses will be antireflection coated but will still have some residual reflected light we can use. The reflections from an initial convex surface will produce a large expanding beam, and the second surface, depending on its shape, may do the same. When the beam is off axis, there will be several beam spots reflected and our task is to overlap them with the incoming beam at the center of the pattern. A horizontal and vertical adjuster on the lens allows precise overlap to be achieved. Often there will be a need for more than one lens—such as for use as a beam expander—and this will require the overlap of reflections from many surfaces. *Always work on one at a time and align that one item to your previously aligned optical axis*. Remember that changing wavelength will likely require a change in the longitudinal focal position of the lens and quite probably a tweak of the alignment.

8 The Shearing Interferometer for Testing Collimation

In Section 3.3, I discussed collimating a beam whereby we seek to produce parallel wavefronts and reduce the beam divergence. It was mentioned that precise determination of the collimation state of a beam must be performed interferometrically. The shearing interferometer (also called the shear plate interferometer) is a device which can do just that and is commercially available. The device makes use of reflections from surfaces on a glass plate producing two displaced but overlapping beams as can be seen in Fig. 17. At the overlap of the beams, an interference pattern is produced and the nature of this pattern is used to determine if the beam is collimated. If the plate is wedged slightly, the interference fringes produced will vary in the direction of the wedge, usually orthogonal to the direction of the shear. Beams with residual focus will have fringes aligned at an angle.

9 Alignment of Near-Infra-Red Beams

Conventional optics made from silica (glass) will have a transmission spectral profile that extends to nearly 2 μm in the near-infra-red (NIR). Thus a system that will operate in the NIR, such as a telecoms system at 1.5 μm, will be able to transmit visible light. The optical components themselves may well be coated to reduce reflections but they will still transmit a visible beam. Aligning a system with a beam you cannot see is an extremely difficult task, so the most sensible approach is, do not do it!

- Align the system components using a visible laser. This will at least allow you to get the components and thereby the optical axis established and aligned.
- Active elements such as lenses, even achromatic lenses, will focus in a different place for visible than for the IR. However when the axis is aligned, you know that you will require a change in focus only.
- NIR systems may well contain optical fibers. Thus you will need to get the alignment laser into the system. By far the easiest way to do this is with a laser, such as a diode laser, that is coupled to a fiber pigtail, which will allow you to just plug it into the system (This is actually a very useful

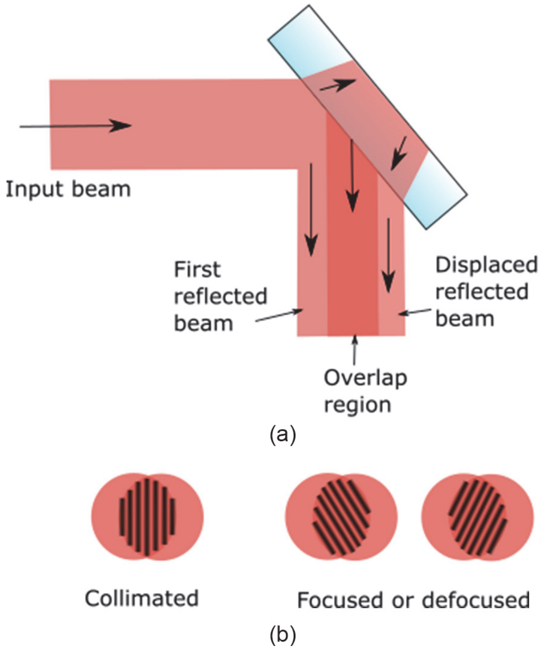

Figure 17 (a) A diagram of a shearing interferometer used for collimation testing and (b) the interference patterns seen when the beam is collimated or has some focus.

laboratory tool anyway as it provides a clean beam that can be used for many alignment tasks). Without this, you will need to revert to focusing a laser into a fiber yourself as in Section 5.

- In some cases, even a visible alignment laser is not the complete answer—for example, if you are using a diffraction grating where light comes off at a different angle. In such cases, you will need a method of viewing where the beam is. This is often done with an IR viewing card. This uses a phosphor which absorbs IR light and glows in the visible. This can give a diffuse indication of the size and position of the beam. The phosphor will need “recharging” with visible light every few minutes. Another option is an IR viewer similar to a night vision device which can provide an image of where bright IR spots are located.
- Bear in mind that detectors that see visible light will most likely not see NIR light and vice versa, so you will need to switch between detectors as you switch between wavelengths.

10 The Retroreflector as a Useful Tool

A retroreflector is an optical element that reflects light back in the same direction that it originated. The effect is seen with highly reflective clothing or road signs

David Benton graduated in Physics from the University of Birmingham in 1989. He completed a PhD in laser spectroscopy for nuclear physics in 1994 and then conducted postdoctoral research in positron emission tomography and then laser spectroscopy for nuclear physics, all at the University of Birmingham. In 1998 he joined DERA which became QinetiQ where he worked on a variety of optical projects. He was the leader of a group building quantum cryptography systems and was involved in a notable 140km demonstration in the Canary Islands. He became Chief Scientist for L-3 TRL in 2010 working on photonic processing techniques for RF applications. He is now at Aston University with a variety of interests including novel encoding techniques, gas sensing and laser detection techniques. He is a member of the SPIE.