Some Practical Implications of Optical Reciprocity for Spectroscopic Instrumentation

In optics, as well as many other disciplines, general principles can serve as powerful tools in both the design and performance analysis of various instrumental applications. Well known principles such as Conservation of Energy, Fermat's Principle, and Optical Reciprocity comprise a few such cases in point. This brief application note will address the last of these three, because its implications and utility can sometimes be misinterpreted.

Reciprocity relations in optics take various forms depending on the level of generality to be addressed. The Helmholz reciprocity theorem [Principles of Optics, sec. 8.3, Born and Wolf] is given in a format applicable to either wavefront or ray optics analysis. We will restrict the attention here to the latter case in order to emphasize the ray picture's utility for most spectroscopic instruments. [Fundamentals of Photonics, Saleh & Teich]. In that special case, if a ray of light traverses a linear optical medium, and is redirected through that medium back along the exit path, it will exactly retrace the incident path through that medium. [See Figure 1] Energy conservation ensures that the net efficiency is identical in either case. Though this statement is straightforward, its implementation must include the practical issue that light sources involve bundles of rays, so an effective path or efficiency analysis requires careful attention to an ensemble of rays, or properly chosen extrema. A series of examples illustrates this effectively.

Optical Reciprocity

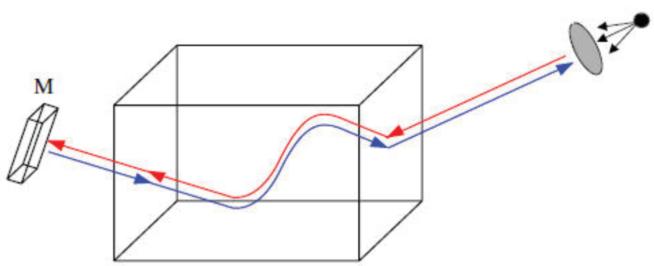

Figure 1

In a ray optics picture, optical reciprocity implies that the path traversed in any medium, will be retraced exactly by a ray initiated along that same path, but in the reverse direction.

Example 1 - Optical Filter

This simple application addresses a beam of collimated light traversing a sample as in Figure 1, but with a collection of parallel rays, incident upon a medium. By reciprocity the return paths and the throughput efficiency would be precisely identical for either incident direction, and this remains so even in the presence of a non-uniform or absorbing index gradient. Note that each incident ray is identifiable with a corresponding ray in the reverse direction.

Example 2 - Diffraction Grating

A significant portion of spectroscopic instrumentation requires these components [Diffraction Gratings, p.189, M.C. Hutley]. The input beam can be taken to be collimated and monochromatic, since generalized cases may be comprised of a (possibly continuous) collection of such rays. An incident beam directed along "zero order", will be dispersed into a number of discreet orders. Reciprocity is simply illustrated by considering one of the "n" diffracted orders. If that diffracted exit beam is re-directed back along itself, the path will be retraced with identical efficiency.

Example 3 - Reflective Filter

Possible confusion is avoided in this case by noting that the exit beam from a reflective filter is by definition on the same side as the incident one, so reciprocity provides no connection between beams incident on opposite sides of such a filter, even if it is partially transmissive. That no such connection is expected is simply illustrated by a single sided mirror.

Example 4 - Phase Conjugate Reflector

This reflective optic device that exhibits the extremely remarkable property that every incident ray is reflected exactly along its incident direction, independent of angle! Note that even a retro-reflecting corner cube fails to meet simple ray reciprocity due to the return ray displacement. Although phase conjugation provides an ideal realization of ray reciprocity, low efficiencies in passive forms, and high complexity for active ones, make it impractical for most spectroscopic work. Successful system applications have nevertheless been implemented in holography, advanced laser feedback design, and certain methods of wavefront restoration. [Optical Phase Conjugation, R.A. Fisher].

Example 5 - Integrating Sphere

We may now examine a case where light rays are present in all possible directions. Despite the apparent difficulty of tracking rays from a scattering surface, even here a simple model can provide many useful results. An integrating sphere with light originating inside and exiting through a small port is well approximated as a black-body source, the port itself acting as a "Lambertian" source that emits into the solid hemisphere, with radiance independent of angle. A loss-free scattering model retaining spectral reflection, is simulated by an inner surface covered by a mosaic of small randomly oriented mirror segments. Thus any ray, after multiple reflection, exits the port in a random (weighted) direction, or is re-absorbed at the source.

As a practical example, the efficiency of using such a sphere as a spectroscopic illumination source, may be compared with the reverse configuration where light is gathered for detection [See Figures 2 A&B]. Either configuration clearly retains the defining useful characteristic of such spheres, the ability to integrate a sample's response to light at all angles of incidence.

To illustrate this we first consider an idealized extreme case, in which the spectrometer is restricted to generate or receive only perfectly collimated light. It is then clear from Figure 2-B (sphere in detection mode) that in the small port limit, nearly all of the light eventually lands on the detector. On the other hand the use of the sphere as the light permits almost no generated light to reach the detection system, since only a negligible portion of the random exiting angles are collimated. Reciprocity arguments apply only to the ray pairs, or wavefront portions, that re-trace their source-detector paths in both directions. Thus the asymmetry in this case must be analyzed in terms of the geometric losses. To consider this in more detail we examine the case to follow, where all components are given physical dimensions, and proper cone angles replace perfectly collimated light.

In a more realistic model, that retains very simple analysis, the source, detector element (resolution limited), spectrally and spatially mode matched spectrometer entrance and exit slits, and the sphere's port, are taken to have the same shape and area. Furthermore, the mono(poly)chromator accepts and emits F# 4 light cones, and the source is Lambertian. It is then straightforward to determine with the aid of Figures 2-A&B, that with correct imaging of the numerical apertures, the net efficiency in these two configurations is in essentially identical. In one case the primary loss is due to the fraction of light emitted from the integrating sphere into a cone of F# 4. In the other, that same loss is incurred by the portion of the source filament's spherical emission that is imaged onto the spectrometer slit, again restricted by the cone angle of F# 4. (For light entering the sphere, the "exit" port loss is of course balanced by the emitting source's absorption factor in the two configurations.) Thus in a configuration simulating an actual implementation, we see that though the two configurations exhibit symmetry in net efficiency, it is not due entirely to reciprocity in this case.

Conclusion

A complete optical system could entail many more critical parameters and constraints besides efficiency and ray geometry. For example, the sample may have a threshold that limits the allowable light flux; in such a case the overall system performance may be largely determined by the detector's response characteristics. Various trade-offs may apply; in certain spectral regions photodiodes permit faster response and data acquisition, whereas PMTs may exhibit a slower but much superior sensitivity, dynamic range, and signal/noise ratio, resulting in significantly greater measurement accuracy.

This brief study focused largely on only one particular principle, however both its utility and limitations were examined. The clear implication is, that to achieve a truly optimized system design, one needs to address all of the crucial performance parameters and constraints of that particular application, and in that process identify and implement relevant general principles.

Integrating Sphere: As Source/Detector

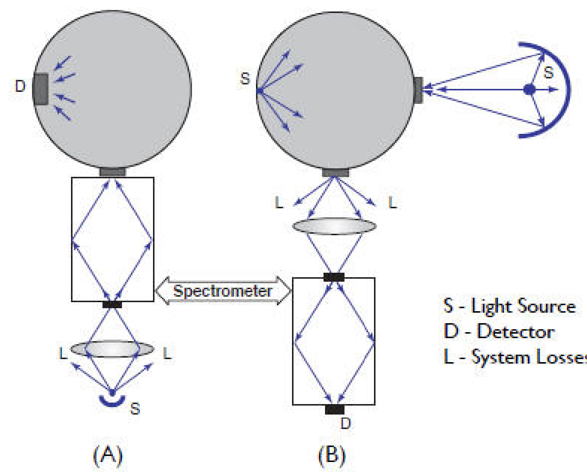

Figure 2

These two configurations illustrate an underlying symmetry with regards to losses (L) when source or detector are located within the sphere itself. The same fixed f # mono(poly)chromator, as well as mode-matched optics are assumed. If the light source and the sphere's exit port emit Lambertian patterns, the geometric system loss is the same in both cases i.e. the ratio of light in the solid cone angle defined by the f # to that of the Lambertian hemi-sphere. In either case it is incurred at the input lens to the spectrometer, in A for illumination and in B for detection.

Other assumptions entail modification. For a source modeled as a spherical emitter, an approximate factor of two loss is introduced in case A. Note that such loss does not necessarily apply to an alternate source location shown in B (outside sphere), since that light emitting geometry is not constrained by the f # of the spectrometer, so reflective non-imaging light concentrators can be utilized.

For related theoretical detail:JOSA-A, Dec 1986, p.2038, E. Wolf and M.Vesperinas