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Introduction and Historical Overview

1.1 WHAT IS QUASIOPTICS?

It is perhaps symptomatic of the specialization of scientific research at the present time that this text should start with a definition of its subject. A fairly widely agreed-upon definition is that quasioptics deals with the propagation of a beam of radiation that is reasonably well collimated but has relatively small dimensions when measured in wavelengths, transverse to the axis of propagation. While at first this may appear to be an implausibly restrictive topic, it actually covers a wide range of situations of practical importance in the design of systems spanning the microwave to submillimeter wavelength range.

Most scientists and engineers are reasonably familiar with geometrical optics, which deals with radiation in the limit that the wavelength $\lambda \to 0$. Starting with the basic rules for the propagation of a ray, representing a perfectly directed bundle of radiation, geometrical optics includes rigorous and complete methods for analyzing optical systems that share the common characteristic that the dimensions of all components (e.g., lenses, mirrors, apertures) are large enough to permit the neglect of the effects of (the actually) finite wavelength.

Diffraction is the tendency for radiation from a source, which is relatively small when measured in wavelengths, to change its distribution as the distance from the source varies. In a limit different from that of geometrical optics, that is, $\lambda \cong$ system dimensions, diffraction effects dominate the propagation of radiation. In these situations, which include the near field of an aperture or antenna, a complex formalism to analyze the behavior of a beam is required, and performing accurate calculations for real systems is relatively time-consuming.

Quasioptics spans the large middle ground between these two limiting cases and thus includes the important and realistic situation of a beam of radiation whose diameter is only moderately large when measured in wavelengths. This allows the elegant theory of Gaussian beam modes and Gaussian beam propagation to be employed. This formalism includes the effects of diffraction within reasonable and generally not highly restrictive limits. The efficacy of Gaussian beam analysis is increased by the considerable variety of microwave and millimeter wave feed horn that radiate beams that are very nearly Gaussian in form. Thus, the radiation from such a device can be represented as coming from the Gaussian beam waist, as shown schematically in the upper panel of Figure 1.1. The action of focusing devices, such as the lens shown in the lower panel of Figure 1.1, is also relatively straightforward to calculate using Gaussian beam formalism.

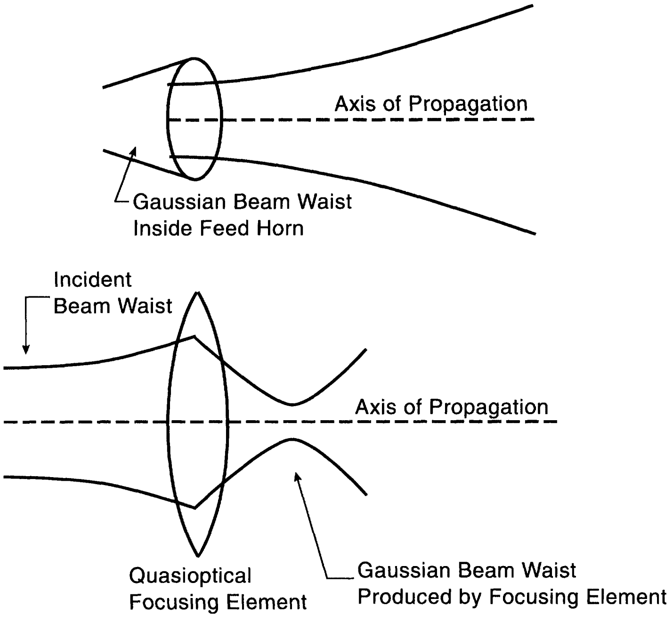

Figure 1.1 *Top*: Gaussian beam produced by feed horn. *Bottom*: Gaussian beam transformation by a quasioptical focusing element.

1.2 WHY QUASIOPTICS IS OF INTEREST

For each portion of the electromagnetic spectrum, various means of propagation that are particularly well suited to the wavelength range have evolved, although there is by no means a unique correspondence. At radio and microwave frequencies, for example, single-mode systems are almost universally employed. The favored means of propagation shifts from coaxial cables with lateral dimensions much smaller than a wavelength at lower frequencies supporting transverse electric and magnetic (TEM) field distributions, to waveguides having dimensions on the order of the wavelength at the higher frequencies. These widely used methods of propagation, along with others including microstrip, stripline, and slotline (to give only a selection), share the characteristic of being used as single-mode transmission media: that is, only a single configuration of the electric and magnetic field can be supported at a given frequency.

Such systems employ metallic conductors and/or dielectrics to obtain the desired field configuration, but both material types result in losses that increase at higher frequencies. The power loss per unit length of dielectric materials generally increases at a rate at least as fast as proportional to frequency; but loss proportional to the square of frequency is found in the millimeter to submillimeter range (cf. [SIMO84], [BIRC94]). Even a low-loss material such as polyethylene has an absorption coefficient of 0.65 dB/cm at a frequency of 500 GHz [TSUJ84]. The loss of rectangular waveguide fabricated from metal of fixed conductivity increases as $(\text{frequency})^{1.5}$ [BENS69]. Surface resistivities measured in practice in the submillimeter region are several times higher than expected from dc values of the conductivity, which can result in waveguide loss considerably in excess of that expected theoretically. While it is true that the physical dimensions of distributed circuits scale with wavelength (inversely as the frequency) and even devices become smaller at higher frequencies, the more rapid increases in metallic and dielectric loss mean that the loss of these single-mode transmission systems becomes excessive for general system use at millimeter and shorter wavelengths (although components may still be constructed using these media).

On the other hand, we may consider taking advantage of the essentially lossless nature of propagation of electromagnetic radiation in free space.[1] However, we first note that because of the previously mentioned restriction that the size of all apertures and components must be much greater than λ, any system that would satisfy the condition of being "purely optical" would be impracticably large for these relatively large wavelengths. Since any collimated beam of radiation increases its lateral dimension D by an amount comparable to its initial value in a distance on the order of D^2/λ, a beam initially having a transverse size of a few centimeters and a wavelength $\approx$ 1 cm will, in a distance of a few tens of centimeters, expand to be of virtually unmanageable size. Thus, we are faced with beams of radiation that are *not* large in their transverse dimensions measured in wavelengths and consequently diverge and have to be refocused to make a complete system. The nature of this refocusing, taking place in the near field of the collimated beam, means that the use of geometrical optics will result in serious errors. Consequently, if we wish to take advantage of the potentially lossless propagation in free space, we need to deal with the diffraction that inevitably accompanies the relatively small beam diameters that are dictated by practical considerations.

Quasioptical propagation using Gaussian beams offers a solution to this problem. In addition to overcoming the formal problem of accurately calculating the behavior of radiation in such systems, it has a number of other advantages that make it a particularly attractive means of transmission. One of these is that result of dispensing with metallic or dielectric transmission lines, interaction with loss-producing materials, is virtually eliminated. As we shall see, quasioptical propagation does require focusing of the propagating beam, but the lenses or mirrors used are relatively well separated from each other, and the loss per unit length over which the beam travels is drastically reduced. As an example, the theoretical attenuation of the TE_{10} mode in WR-4 rectangular waveguide at 250 GHz is approximately 12 dB/m. This can be compared to the loss measured by Lynch [LYNC88] in a relatively constrained quasioptical Gaussian beam waveguide system at this frequency, which used a series of Teflon lenses, of 1.5 dB/m. In addition to outstandingly low loss, quasioptical systems can handle multiple polarizations and can operate over very large bandwidths; both these characteristics arise from the absence of boundary conditions that introduce dispersion into waveguides and millimeter and submillimeter wavelength transmission media of other types. Quasioptical systems can distribute power over a region at least several wavelengths in size, while single-mode transmission line systems are restricted to dimensions less than

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[1] Only at frequencies at which resonant molecular transitions occur is atmospheric absorption significant on a laboratory scale. Strong lines in the submillimeter region have absorption coefficients ranging from a few decibels per meter up to tens of decibels per meter.

or equal to a wavelength. In quasioptical systems, the absence in dielectrics and at metallic conductors of breakdown that would otherwise be present results in the possibility of a significant increase in power-handling capability. In addition, we have the possibility of using many devices that can share the power to be handled and can also dissipate power more effectively, as a result of the larger space available.

Quasioptical systems can have considerable imaging ability, meaning that a single set of lenses, mirrors, and other components can operate on different beams while preserving their independent characteristics. This capability is, of course, akin to that of geometrical optics systems and is a characteristic that is totally absent in single-mode transmission media. The imaging capability of quasioptical systems is in general more restricted than that of geometrical optics systems, but the relatively new topic of quasioptical imaging promises to further enhance the desirability of this propagation medium.

1.3 HISTORICAL OVERVIEW

In a general sense, quasioptics dates back to the earliest experimental studies of radio waves carried out by Heinrich Hertz in Karlsruhe, Germany, during the late 1880s. Hertz was not able, in his initial experiments at a frequency of 50 MHz (50×10^6 cycles per second corresponding to $\lambda = 600$ cm), to observe focusing action by cylindrical parabolic antennas [BRYA88]. This failure can be understood in terms of the size of his apparatus (≤ 200 cm); being considerably smaller than the wavelength of the radiation employed, this aperture could act only as a point source.

After modifying his equipment for generating and detecting radiation, Hertz succeeded, in 1888, in operating at a frequency of 500 MHz. The 60 cm wavelength was thus several times smaller than the dimensions of his apparatus, and the emitted radiation could, to a limited extent, be collimated by the parabolic cylinder reflectors employed for this purpose. With this apparatus Hertz studied a number of effects which, until that time, had been observed only at the much shorter wavelengths characteristic of infrared (thermal) and visible electromagnetic radiation. These included polarization, carried out with wire grid polarizers remarkably similar to those in use today at 1000 times higher frequency than used by Hertz (cf. Chapters 8 and 9), reflection from a metal surface, and refraction by dielectric materials. Hertz was able to make the first measurement of an index of refraction at microwave frequencies.

While Hertz's experiments were primarily intended to show the similarity between radio waves (electromagnetic waves having wavelengths on the order of a meter) and visible light, it is interesting from our perspective to realize that since his apparatus was only two to three wavelengths in size, he had really developed the first quasioptical components. The beam divergence was not immediately apparent because the distances available in Hertz's laboratory were less than the far-field distance (approximately 6 m).

Another very interesting early experimentalist who used quasioptical apparatus in investigations of microwave and millimeter wave propagation and interaction with materials was Sir Jagadis C. Bose, who carried out studies of plant physiology and other fields in India at the end of the nineteenth century. Employing a type of spark gap transmitter, Bose was able to produce radiation at frequencies between 12 GHz (1 GHz = 10^9 Hz) and 50 GHz ([BOSE27], Chapter IX, pp. 77–101). He was very much in favor of using these high frequencies to obtain directed beams of radiation with relatively small apparatus. To this end, he employed lenses for beam collimation and used a collecting funnel (very similar to a rectangular feed horn) in front of his improved detector.

Bose carried out many of the same experiments reported by Hertz, but with an obviously more compact benchtop apparatus. In addition to measurements of the index of refraction of natural materials (including glass with $n = 2.04$ and sulfur with $n = 1.73$), he experimented with a wide variety of naturally occurring anisotropic materials and developed a number of artificial anisotropic materials. Bose demonstrated that his outstretched fingers acted as a polarizer, as did a book![2]

Bose's experiments were carried out in Calcutta, and while he did give lectures to the Royal Institution in London, his impressive results do not appear to have resulted in any ongoing research at short wavelengths. His investigations did prompt significant improvements in technology for generation and detection of microwave and millimeter wavelength radiation, as well as further reinforcing the commonality of the physics of electromagnetic radiation over a wide range of frequencies.

Another example of relatively isolated research at short radio wavelengths is that of A. Glagolewa-Arkadiewa, who worked in Moscow. Her work concentrated on generation of radiation at submillimeter wavelengths, employing an oscillator that included an induction coil, but quite distinctively, a mixture of fine brass or aluminum filings suspended in mineral oil. It was felt that the size of the filings affected the radiation produced by the discharge. The energy was radiated by wires located near the focus of a paraboloidal reflector and collected by a thermal detector at the focus of a second mirror [GLAG24a], [GLAG24b]. Glagolewa-Arkadiewa measured the wavelength of the radiation using a type of interferometer and found from analysis of the interferograms that a range of wavelengths was produced, covering the range of 50 mm to 82 μm!

With a few such exceptions, the early part of the twentieth century witnessed great progress in radio frequency technology, but relatively little work at very short radio wavelengths. At that time, 10 m wavelength (30 MHz frequency) was the upper limit for commercial broadcasting. A relatively radical suggestion was made by E. Karplus to use the region between 10 m and 1 μm wavelength for communications [KARP31]. While he referred to radiation in this spectral range as "quasi optical waves," the technology he discussed was essentially extension of vacuum tube circuitry used at longer wavelengths, although thermal radiation was also considered. One interesting technique that Karplus mentioned that *has* become widespread at short-millimeter wavelengths is the use of harmonics of oscillators (i.e., harmonic generation).

[2] Working at a frequency of 43 GHz ($\lambda = 0.7$ cm), I have, to a certain extent, been able to duplicate Bose's finding that a book can act as a microwave polarizer ([BOSE27], Chapter IX, p. 99). Several books and catalogs with apparently plain and coated paper were studied. They shared the characteristic that when measured with the direction of propagation in the plane of the pages (with the electric field either in this plane or perpendicular to it), the attenuation traversing 15 to 25 cm of paper was excessive for both polarizations ($>$ 22 dB). On the other hand, folding a newspaper so that the thickness along the beam was approximately 5 cm and clamping it so that there were approximately 100 pages per centimeter resulted in a device with reasonably low loss. For the electric field perpendicular to the sheets of paper, the attenuation was approximately 10 dB, while for the electric field in the plane of the paper, the attenuation exceeded 20 dB. This is reasonably consistent with Bose's qualitative description of his results, suggesting that the pages of his book were relatively well separated. It is not obvious whether the action can be best described in terms of a very lossy parallel plate polarizer or in terms of propagation in a lossy anisotropic dielectric structure. Bose did find that a polarizer made by placing sheets of tinfoil between the pages resulted in a polarizer with better performance than the book alone, as seems quite reasonable ([BOSE27], Chapter X, p. 105).

While antenna technology advanced, there was not a great deal of interest in producing collimated or focused beams of radiation. Coaxial transmission lines were extensively developed and used at relatively low frequencies. Waveguides were studied as well, and Southworth and his colleagues at Bell Laboratories and Barrow at MIT [PACK84] demonstrated their effectiveness as transmission media for microwaves. Microwave technology advanced remarkably during the Second World War and subsequently was employed for communication systems. The increasing demand for bandwidth in the 1960s and 1970s spurred a renewal of millimeter wavelength studies. The preferred medium for transmission over long distances was expected to be oversized waveguide employing the circular electric (TE_{01}) mode for which the attenuation *decreases* as the frequency *increases* [SOUT36], [KING61].

The renaissance of interest in quasioptics actually derives from the development of components and systems at optical wavelengths, in contrast to the early work discussed above. The primary driving force appears to have been development of improved communication systems. Spurred by the availability of the laser as a source of coherent radiation, a variety of different schemes were investigated for communication links. These involved free-space, periodically guided, and continuously guided transmission schemes [KOMP72]. The most relevant research for Gaussian beams and quasioptical transmission was concentrated in the areas of laser resonators and transmission through sequences of lenses or mirrors.

The pioneering work by Schawlow and Townes proposing visible-wavelength masers (soon to be called lasers) indicated the importance of resonant cavities many wavelengths in size [SCHA58]. In a system employing such a multimode cavity (rather than a single-mode cavity characteristic of radio or microwave frequencies), diffraction could be utilized to discriminate against all but a single desired mode, thus resulting in a system having a spectrally and spatially well-defined output. However, the distribution of the electric field within a cavity or at its partially reflecting mirrors remained to be determined. The first operating lasers were reported within the next few years, and the importance of being able to calculate the field distribution within a laser cavity as well as the loss due to diffraction at the end mirrors inspired several different avenues of research.

Fox and Li [FOX60], [FOX61] adopted a numerical approach. By following the diffraction of a beam bouncing back and forth between reflecting mirrors of finite dimensions, they were able to show that after a number of reflections, the field distribution achieved a form that no longer varied except for an overall multiplicative factor. In this sense, the field distribution obtained is a "mode" of the optical cavity, although the mode is not a unique field distribution like that in a microwave cavity. The numerical results of Fox and Li indicated that the cavity mode has its energy density concentrated on the axis of symmetry of the cavity, and that the diffraction loss per transit is much lower for a confocal cavity (radius of curvature of the mirrors equal to their separation) than for one utilizing plane mirrors.

Boyd and Gordon [BOYD61a], [BOYD61b] developed an analytic solution of the diffraction problem that was, however, restricted to confocal cavities. These authors were able to show that for a rectangular resonator with low diffraction loss (field concentrated in a region considerably smaller than the size of the mirrors), the modes have their electric field oriented transverse to the axis of the resonator and have an amplitude distribution in each transverse dimension given by a Gaussian multiplied by a Hermite polynomial. Numerically and analytically, it thus became clear that a Gaussian field distribution (or Gaussian beam mode) was the natural one for a resonant cavity of finite dimensions compared to the wavelength.

Almost simultaneously, work on another aspect of optical communication systems was highlighting the importance of Gaussian beams. This was the analysis of a sequence of focusing elements (lenses or mirrors) to be used to transmit a beam of radiation over relatively long distances. The lowest loss field distribution in a system consisting of a sequence of axially symmetric phase transformers was found by Goubau and Schwering [GOUB61] to be essentially a Gaussian. Experimental verification of such a "beam waveguide" operating at a frequency of 23 GHz was published at the same time by Christian and Goubau [CHRI61]. The equivalence between the resonator and the beam waveguide was first addressed theoretically by Pierce [PIER61] and was exploited experimentally by Beyer and Scheibe [BEYE63]. Degenford et al. [DEGE64] demonstrated a reflecting beam waveguide at 75 GHz and also used a resonator technique to verify the extremely low loss predicted for this transmission system. Measurements on beam waveguides at optical wavelengths were carried out by Christian, Goubau and Mink [CHRI67], and Gloge [GLOG67]. While beam waveguides have not been used for long-distance transmission, this work, together with that on resonators, firmly established Gaussian beam modes as a critical element of quasioptical system design.

1.4 ORGANIZATION OF THIS BOOK

Gaussian beam analysis allows rapid and efficient design of quasioptical systems. It is, in many cases, a formalism sufficiently accurate and complete with which to proceed directly to the fabrication of system hardware. In other cases, the Gaussian beam analysis can be considered as the starting point for a more rigorous treatment using the complete apparatus of diffraction theory; as such, it is still a very effective method for initial system specification.

For these reasons, we treat quasioptics and Gaussian beam propagation as essentially interchangeable in this book. Where appropriate, the extensions to the Gaussian beam analysis presented are covered in limited detail, or indicated through references to these treatments. In Chapter 2 we derive the basic Gaussian beam propagation formulas, and in Chapter 3 we consider the transformation of Gaussian beams by lenses and mirrors. The coupling between Gaussian beams, treated in Chapter 4, is a significant issue for the analysis of many quasioptical components as well as for setting the tolerances in quasioptical systems. Some practical aspects of the construction of quasioptical focusing elements are discussed in Chapter 5. In Chapter 6 we analyze Gaussian beams and antenna feed systems, emphasizing relatively large antennas. In Chapter 7 we treat the Gaussian beam analysis of small radiating systems, primarily feed horns used at microwave and millimeter wavelengths.

Chapters 8 through 10 deal with quasioptical components. Chapter 8 deals with components that are not primarily frequency selective—including delay lines, polarizers, ferrite devices, attenuators, and absorbing loads. Chapter 9 focuses on frequency selective devices—the quasioptical filters and diplexers of many types that are a powerful reason for dealing with quasioptical systems. This chapter also includes a discussion of quasioptical resonators. Chapter 10 covers active quasioptical devices—those combining quasioptics with (primarily) semiconductor structures performing all the functions expected of active devices, but with the added advantage of greater power handling capability and efficient, direct coupling to quasioptical beams. Chapter 11 deals with quasioptical system design from a relatively practical viewpoint, starting with the general rules and methodology, and including examples that illustrate some of the wide variety of applications of quasioptics.

1.5 BIBLIOGRAPHIC NOTES

The development of quasioptical techniques during recent years can be followed by means of a number of review articles. Some of the relatively early papers, including [HARV59], [CULS61], and [FELL62], largely predate the development of Gaussian beam mode theory but deal with diffraction and quasioptical systems. [KOGE66] provides a compact review of basic Gaussian beam theory, while [GOUB69] stresses derivations of major results. [TREM66] supplies a very complete bibliography of earlier work. [GARN69], [GOLD82], and [GOLD92] stress operational principles of quasioptical components. The text by Siegman [SIEG86] has several excellent chapters devoted to Gaussian beam propagation, while specific aspects of Gaussian beams and quasioptical components are covered in a book [LESU90].

Beam waveguides have not seen significant use in long-distance communications systems, despite their apparent potential; one interesting scenario is described by [ARNA75]. A comprehensive overview, with many references to early work, is [GOUB68]. Beam waveguides are being used to an increasing extent in large satellite ground station antennas, as well as in conjunction with radio astronomical telescopes, and Gaussian beam analysis is fundamental for understanding their operation.

Analysis of multimode quasioptical resonators has proven to be a subject of continuing activity. This is due in part to its inherent interest and in part to the many applications of such resonators to oscillators (cf. [STEP88]) and to systems used for materials properties measurement (cf. [CULL83]).