Calculating component coupling coefficients

Kevin J. Garcia

SIMULATION SOFTWARE

An important element of telecommunications component modeling is the ability to simulate sources and components in order to optimize the efficiencies—or power transfer—between these systems. For example, it is very important to maximize the amount of power coupled from the laser into a single-mode fiber to minimize power loss. To do so, the mode of a laser diode and coupling system should match the mode of the single-mode fiber it is entering. This calculation is called the coupling coefficient calculation and is dependent on a number of parameters associated with the source, the coupling optics, and the fiber.

Fortunately there are common threads that bind the calculation of the system's coupling coefficient together. These common threads are found in fundamental characteristics that specify the behavior of electromagnetic radiation—coherence, polarization, amplitude, and phase.

Calculating coupling efficiencies is important not only in the case of a single-mode fiber but for other components such as spectrally tuned WDM systems. Coupled fields and coupling coefficients can be computed in some but not all commercially available software programs.

> Achieving good system performance begins with light transmitted through components and fiber with the maximum possible efficiency. In this example, the efficient coupling of a light source to a fiber is modeled to find the best position for the fiber, light source, and ball lens.

method of simulating field propagating is important because it is actual optical fields that are used in an overlap integral to compute the coupling efficiency.

As the Gaussian rays propagate through the optical system, their amplitudes and phases are changed respectively by the local diattenuation and aberration of the optical elements. In this sense each Gaussian beam samples a local area of the optical surface, and the summation of all the Gaussian beams constitutes the polarization changes, power losses, and aberrations imparted to the optical field by the surface. Each Gaussian beam—and thus the entire wavefront—is then rigorously propagated through virtually any optical system.

The resulting field can be calculated and displayed at any location/skew plane within the optical system and not just near focus. This capability can be done without any complex matrix techniques, Fourier or Fresnel transforms, or integrals. Furthermore, the effects of multiple beam paths and ghost imaging are straightforwardly simulated because geometric rays can be easily split at interfaces with nonzero reflection and refraction coefficients.
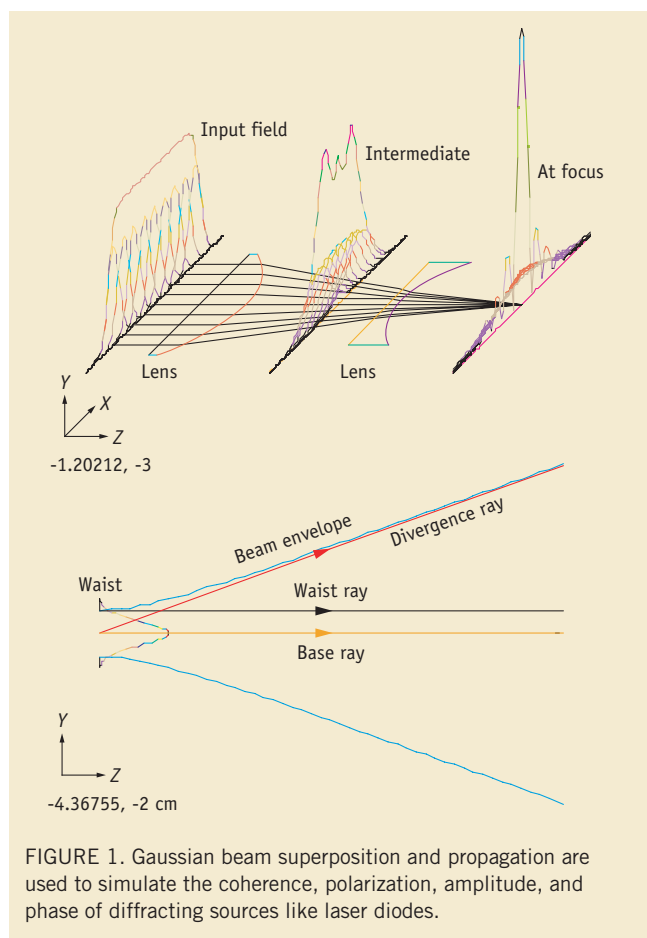
PHYSICAL OPTICS TECHNIQUE

The technique used in ASAP (Breault Research Organization; Tucson, AZ) to simulate the coherence, polarization, amplitude, and phase of diffracting sources like laser diodes—and in general other physical optics phenomena—is called Gaussian beam superposition. The Gaussian beam superposition algorithm models arbitrary optical fields as a summation of fundamental Gaussian beams. The superposition algorithm is similar to Babinet's principle except that Gaussian beams are used as the basis functions (Babinet's principle states that the diffraction patterns produced by complementary screens are identical).

The Gaussian beams are each represented by a set of real rays describing the coherence, polarization, amplitude, and phase of the Gaussian, which may be traced through the optomechanical system. This set of rays characterizes the near-field and far-field properties of a Gaussian beam. It is possible to superpose the ray trace information from the individual Gaussian beams to recreate an arbitrary optical field at any position in space (see Fig. 1). Understanding this

COUPLING CALCULATION

The coupling coefficient is a mathematical representation of how the mode of the incident light "couples" or is "accepted" into an optical system such as a fiber. The coupling coefficient is the fraction of the power of the incident optical field mode that is coupled into the propagating mode of the optical system.

Light propagating in single-mode fibers, and in general, in very small waveguides, is a purely diffraction phenomenon. Light propagation in the fiber can be described in the form of transverse modes. The superposition of the modes yields the resulting field. This behavior is mathematically similar to the Gaussian beam superposition algorithm. Complex optical fields in it are represented by the superposition of a mode, in this case a fundamental Gaussian beam, whose propagation is described by a set of real rays. The fundamental Gaussian beam is one mode of the family of Hermite Gaussian beams.

The fiber will support the propagation of only certain mode types. This selection is dependent on the geometry and optical properties of the fiber. Furthermore, the modes that are excited in the fiber are

FIGURE 1. Gaussian beam superposition and propagation are used to simulate the coherence, polarization, amplitude, and phase of diffracting sources like laser diodes.

dependent on the incident light. Depending on how the modes in the incident light match those that are supported by the fiber determines how much light is coupled into the fiber and will propagate through the fiber. The incident light is sometimes said to excite a certain mode behavior in the fiber. Single-mode fibers allow only one type of mode excitation, which is approximately Gaussian in shape. Multimode fibers can be excited by multiple modes.

Coupling calculations for lens design codes vary, with many of the calculations based upon Wagner and Tomlinson's paper, "Coupling efficiency of optics in single-mode fiber components" [*Appl. Opt. 21*, 2671 (1982)]. Wagner and Tomlinson's method requires computing the overlap integral of the far-field system amplitude distribution and the fiber amplitude distribution. This result is then multiplied by the coherent optical transfer function (OTF) of the coupling system.

The method used in ASAP calculates an overlap integral to compute the coupling efficiency; however, it does this calculation by directly operating on the amplitude distribution from the system and a mathematical distribution describing the fiber mode. ASAP's mathematically normalized coupling calculation is operationally defined as follows:

$$\eta = c^2 = \frac{\left|\iint \psi_{sys}(x,y)\psi^*_{fiber}(x,y)dxdy\right|^2}{\iint \psi_{sys}(x,y)\psi^*_{sys}(x,y)dxdy \iint \psi_{fiber}(x,y)\psi^*_{fiber}(x,y)dxdy}$$

Here ψ_{sys} is the optical field of the input light and ψ_{fiber} is the fiber optical field mode.

The diattenuation and phase changes normally represented in the OTF of the system are inherently present in the system amplitude distribution through the individual Gaussian beams. The individual Gaussian beams discrete sampling of the power losses and aberrations as a function of field and pupil each contribute to the superposed system amplitude.
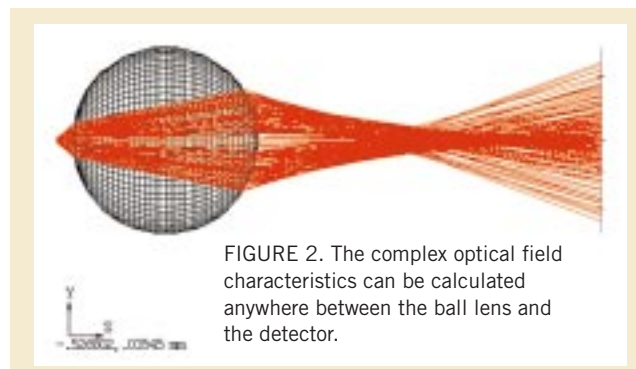
BALL LENS COUPLING

The ball lens coupler is probably the simplest optical coupling system outside of direct or butt coupling. In direct or butt coupling, the laser is placed directly against the fiber. The ball lens is symmetric so the orientation of the lens is irrelevant. However, other factors such as fiber positioning are relevant and will affect the coupling efficiency.

A symmetric ball optical system has many advantages but it does impart a large amount of spherical aberration to the laser diode wavefront. In fact, spherical aberration is really the only aberration present because the extremely small fiber cores limit off-axis aberrations. The ball lens couplers are typically used at large magnifications with small diameters and large refractive indices in order to minimize the effects of spherical aberration. This aberration changes the modal behavior of the light from the laser diode and therefore the coupling of the laser diode light into the fiber.

The ball lens system is set up for a −4X magnification. The focal length of the ball lens is actually slightly less than the ball radius and is therefore inside of the ball lens. The laser diode waist of 1.5 µm is magnified to approximately 6 µm at the fiber. The laser diode is placed at the appropriate distance in front of the ball lens. The detector is placed beyond the −4X Gaussian image plane to show the geometric caustic primarily due to spherical aberration in the ray trace plot.

An optical field actually exists everywhere in between the output of the ball lens and the detector. Both the diffraction and geometric envelopes or caustics are illustrated in Fig. 2. We can calculate the complex optical field characteristics anywhere in between these two points. So even though the detector plane is not at the plane of −4X magnification, the optical field can still be calculated at this point.

In fact we can calculate the optical field along the axis to see the diffraction envelope or caustic. The complex, optical field computed at the plane of −4X magnification is used in the overlap integral. The overlap integral is computed using this field and the fiber mode field

FIGURE 2. The complex optical field characteristics can be calculated anywhere between the ball lens and the detector.

Coupled fields

Energy for Z = 1.47

4.643E-02

8.625E-05
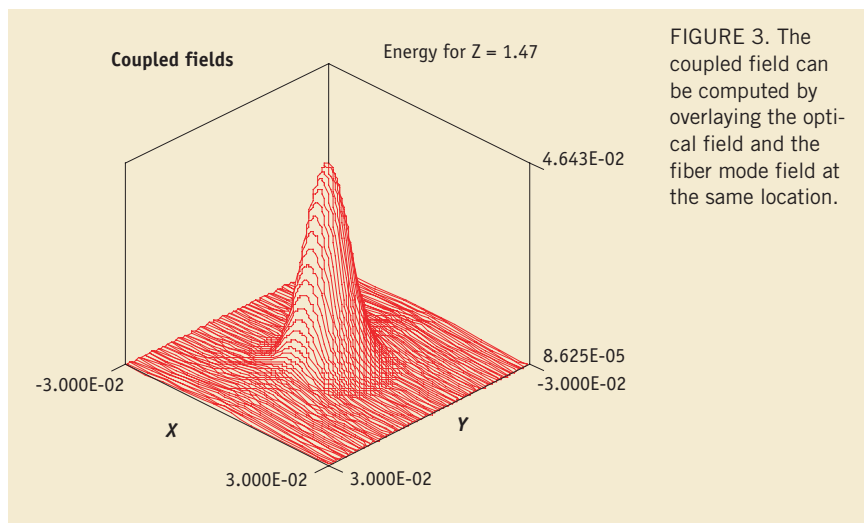
-3.000E-02

-3.000E-02

3.000E-02

3.000E-02

X

Y

FIGURE 3. The coupled field can be computed by overlaying the optical field and the fiber mode field at the same location.

computed at the same location (see Fig. 3).

The coupling efficiency for our –4X magnification is approximately 36.5%. A fundamental question confronting all of these types of systems is where to place the fiber for maximum coupling efficiency. This position determines where the maximum amount of light from the source is coupled into the fiber, and it is usually not in the plane of the best geometric focus.

Diffraction theory is really necessary to properly compute the plane of optimum coupling efficiency. We can find this position, if it is not the current position, by using a parametric iteration technique. A macro language allows us to automatically change the fiber position while re-comput-

Coupling efficiency

70
60
50
40
30
20
10
0

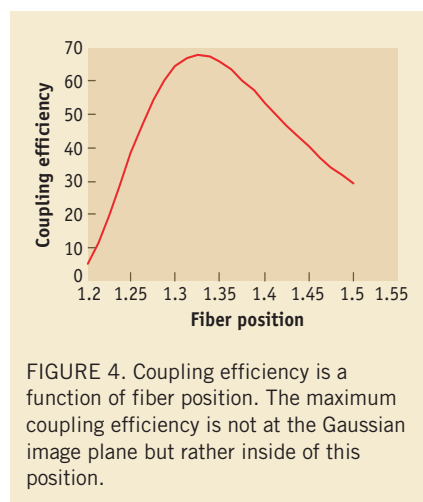1.2   1.25   1.3   1.35   1.4   1.45   1.5   1.55

Fiber position

FIGURE 4. Coupling efficiency is a function of fiber position. The maximum coupling efficiency is not at the Gaussian image plane but rather inside of this position.

ing the coupling coefficient at each new fiber position.

The coupling efficiency can then be plotted as a function of fiber position (see Fig. 4). This calculation can be extended to source alignments, divergences, optical system parameters (radii, thickness, rectilinear positions), fiber parameters, and even ghost reflections off of the fiber. Other common telecommunication components such as aspheric coupling lenses, diffraction gratings, and gradient index optical components (GRINs) also can be simulated in ASAP.

ASAP's Gaussian beam superposition algorithm, with its ability to simulate the coherence, polarization, amplitude, and phase of an optical field, is a powerful and flexible technique that allows you to simulate the physical optics behavior of a wide variety of telecommunication optical systems in the bulk. The Gaussian beam superposition algorithm combines geometrical with physical optics by joining the unique capability and usefulness of geometrical ray tracing with the physical effects of diffraction, interference, and polarization.

WDM

Kevin J. Garcia is a private optical engineering consultant who can be reached at 520-886-4036; e-mail: k_j_garcia@msn.com.