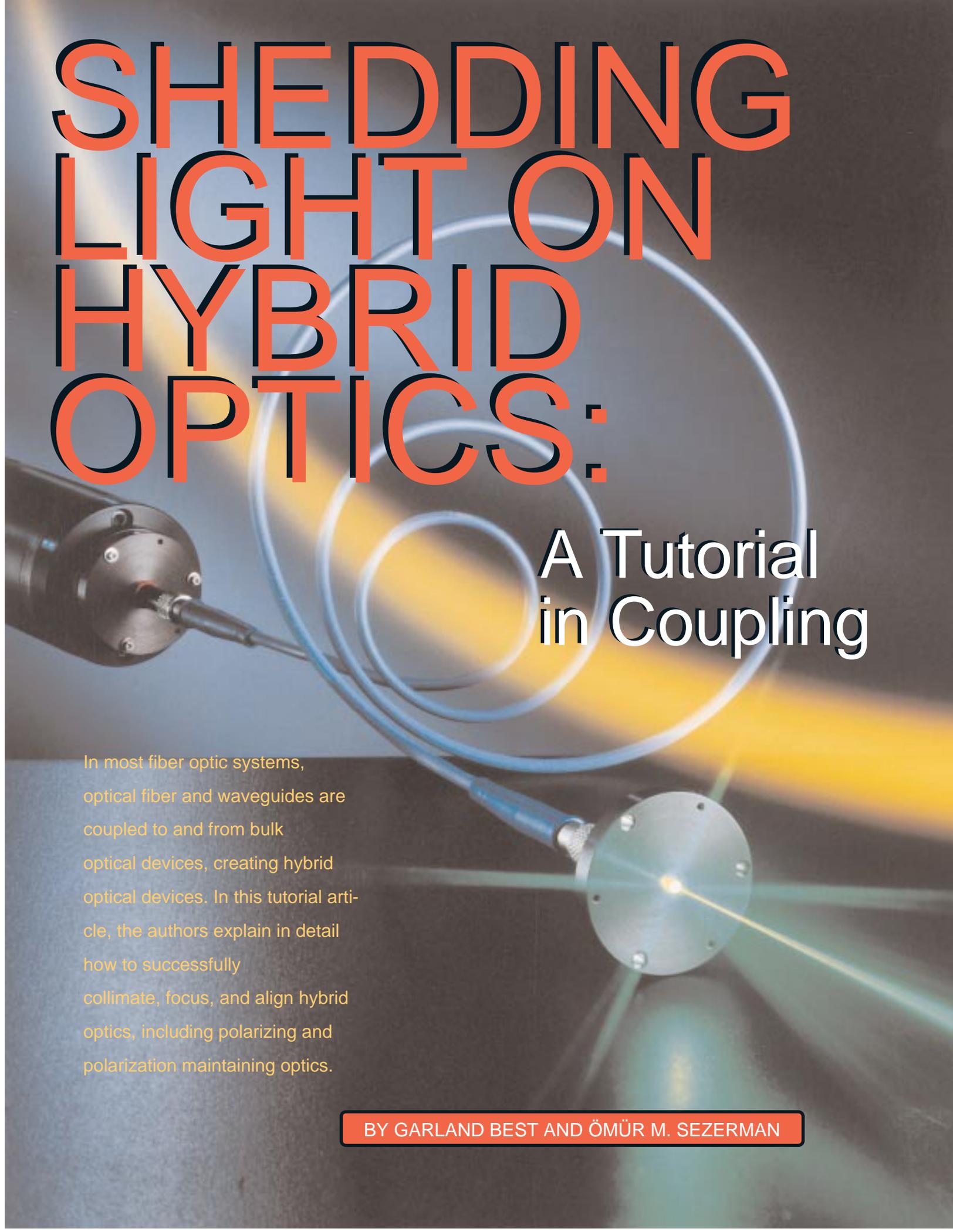


# SHEDDING LIGHT ON HYBRID OPTICS:



## A Tutorial in Coupling

In most fiber optic systems, optical fiber and waveguides are coupled to and from bulk optical devices, creating hybrid optical devices. In this tutorial article, the authors explain in detail how to successfully collimate, focus, and align hybrid optics, including polarizing and polarization maintaining optics.

BY GARLAND BEST AND ÖMÜR M. SEZERMAN

**H**ybrid optics /hī'brid óptiks/, n.pl. 1. the combination of fiber optics, waveguides, or integrated optics with bulk or free space optics to create new optical devices.

Each year, new and unique optical components appear in the marketplace. Advancements are constantly occurring in laser diodes, modulators, delay lines, filters, integrated optics, and other components. Many of these components have applications in the field of fiber optics. However, most of these devices are free space, or bulk, optics. Their optical characteristics are very different than those of optical fiber and waveguides. Therefore a basic task in the fiber optics industry is to couple light from an optical device into a fiber or waveguide, or from a fiber into an optical device.

To that end, one must be able to accomplish three fundamental tasks. First, one must be able to transform highly divergent light from fibers and waveguides into collimated beams usable with bulk optics. Second, one must be able to transform collimated beams into tightly focused spots that match the properties of waveguides and optical fibers. And third, one must be able to precisely align optics to effectively couple light from one medium to another. In this paper, we discuss the technical aspects of all three of these tasks.

#### Collimation

Collimation is the act of taking the diverging output of a waveguide or fiber and converting it into a beam of parallel light. This is done by placing the endface of the fiber or waveguide at the focal plane of a lens. Figure 1 shows this using a fiber. In practice, there is no such thing as a truly collimated beam, as all beams will spread out after traveling a sufficient distance.

If we know the characteristics of the waveguide and lens being used, then we can predict the collimated beam behavior with simple ray optics. If the focal length of the lens is given by  $f$ , then the collimated beam characteristics are given by

$$\begin{aligned} \text{BD (mm)} &= 2.3 f \text{ (mm)} \text{ NA} \\ \text{DA (mrad)} &= a \text{ (}\mu\text{m)} / f \text{ (mm)}. \end{aligned}$$

Where  $a$  and  $\text{NA}$  are respectively the mode field diameter (MFD) and numerical aperture (NA) of the waveguide, and  $\text{BD}$  and  $\text{DA}$  are the beam diameter and full divergence angle of the collimated beam. The divergence angle is measured in terms of milliradians ( $1 \text{ mrad} = 0.057^\circ$ ).

One point that is immediately obvious is that large waveguides do not collimate well. If you try to collimate a 500- $\mu\text{m}$  core fiber with a 5-mm focal length lens, the beam will spread at about a  $6^\circ$  full-angle. This is probably not much better than what you started with.

One also has to be careful how one defines the NA and MFD. Laser manufacturers define their beam in terms of Gaussian beam characteristics, defining the beam size at

the point where the intensity drops to 13.5% ( $1/e^2$ ) of the peak intensity. Laser diode manufacturers speak instead in terms of full-width at half-maximum (FWHM) levels.

In multi-mode fibers, one can simply use the core diameter as the MFD, and use the refractive indices of the fiber core and cladding to calculate the fiber's NA. The formula to use is

$$\text{NA} = (n_{\text{co}}^2 - n_{\text{cl}}^2)^{1/2}$$

where  $n_{\text{co}}$  is the index of refraction of the core, and  $n_{\text{cl}}$  is the index of refraction of the cladding.

With single-mode fibers, using the refractive indices of the core and cladding to define the NA can cause significant errors in the calculation of the beam diameter. A more accurate technique is to treat the output of the fiber as a Gaussian source, and calculate the NA using

$$\text{NA} = 2l/\lambda$$

where  $l$  is the wavelength of the light, expressed in microns. This NA value can be up to 33% smaller than the value listed by some fiber manufacturers.

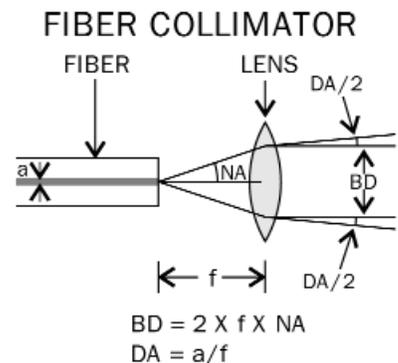
Ensure that the optics used to collimate the waveguide output do not cut off part of the beam. A good rule of thumb is to select optics with an NA at least 50% larger than the NA of the waveguide being collimated. This will ensure over 99% transmission through the optics, ignoring internal reflections.

The choice of lens is also important to ensure optimum performance. Graded index (GRIN) lenses are commonly used, because of their low-cost and ease of handling. In broadband applications, achromatic lenses are best. Other common choices include ball, aspheric, and simple plano-convex and biconvex lenses.

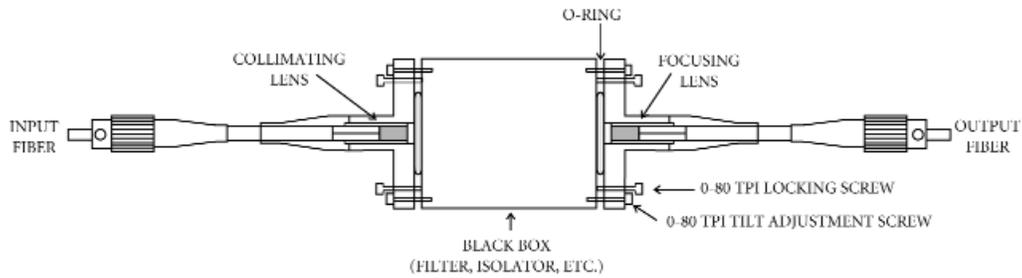
#### Focusing

Essentially, focusing is the same as collimating, only in reverse. You have a collimated beam, with a known beam diameter,  $\text{BD}$ , and divergence angle,  $\text{DA}$ . You wish to couple this light into a fiber or waveguide, with a mode field diameter,  $a$ , and numerical aperture  $\text{NA}_{\text{fiber}}$ . To achieve efficient coupling, two conditions must be met. The focused spot diameter,  $\text{SD}$ , from the focused beam should be less than or equal to the mode field diameter of the waveguide, and the NA of the focused beam,  $\text{NA}_{\text{rays}}$ , should not exceed the NA of the waveguide,  $\text{NA}_{\text{fiber}}$ .

Given a lens with a focal length  $f$ , one can calculate



**Figure 1.** Operating principle of a fiber collimator.



**Figure 2.** Pigtail of fiber optic black boxes.

the focused spot properties using

$$SD (\mu\text{m}) = f (\text{mm}) \sin \theta$$

and

$$NA_{\text{rays}} = \text{BD} (\text{mm}) / 2f (\text{mm}) \quad NA_{\text{fiber}}$$

For multi-mode fibers, a range of focal length lenses can be found that can meet the conditions listed above. If possible, try to select optics that can achieve values for SD and  $NA_{\text{rays}}$  less than or equal to 70% of the maximum allowable values. At the same time, do not focus the spot to a size less than 30% of the fiber core. In high-power applications, this may cause the fiber endface to be burnt.

For single-mode fibers and waveguides, the choice of lens focal length is more critical. Only one focal length can be found that can meet both requirements for spot size and NA.

One problem that often arises is how to focus a circularly symmetric beam into a rectangular waveguide. In this case, the mode field is not circular, but elliptical, with a width,  $w$ , and height,  $h$ . Although corrective optics do exist to circularize such fields, they are often expensive and cumbersome to use. One approach is to work with an effective mode field diameter,  $a$ , given by  $a^2 = wh$ . With this approach, coupling efficiencies over 45% can be routinely achieved with waveguides having 3:1 aspect ratios.

The equations given so far assume that the focusing

optics are at or near the beam waist. As mentioned earlier, all beams diverge, so the question becomes how far away from the beam waist are the given equations valid? Again, as a rule of thumb, excess losses do not become significant until the beam diameter at the lens is  $> 40\%$  than the beam diameter at the waist. Outside of this range a more detailed analysis of the opti-

cal system must be performed to devise an arrangement to minimize losses.

In addition, the quality of the focused spot depends greatly on the quality of both the collimated beam and the focusing optics. The equations shown so far give only the theoretical limit on the minimum spot size, NA, etc. The actual measured values may be significantly larger, depending on the optics used. Care should be taken on this point.

#### Alignment

Having chosen the collimating and focusing optics to use in a hybrid system, the issue becomes how to align the optics to minimize losses. The standard industry technique is to first focus the light from a device to a spot about the same size as the waveguide MFD. The waveguide is then precisely positioned in free space until the endface of the waveguide is at the focal point. Since telecommunications systems deal with MFDs of only 10  $\mu\text{m}$  or less, positioning equipment capable of submicron resolution along all three axes must be used to align the waveguide. Such equipment is bulky, expensive, and difficult to use.

An alternative technique is to first attach the lens to the waveguide to produce a collimated beam in free space. This can be done economically, with minimum equipment. The lens may be either permanently attached to the waveguide, or, in the case of fiber optics, attached via an industry standard connector. The issue then is to align the collimated beam from the free space optics with the collimated beams produced by the waveguides.

By working with collimated optics, we don't have to worry about the distance between the waveguide and the bulk optics. In addition, the dependence on lateral alignment is greatly reduced, and errors on the order of tens of microns are not an issue when dealing with one-millimeter diameter beams.

Naturally you don't get something for nothing. While reducing the effect of lateral misalignment, the sensitivity to angular misalignment has been greatly increased. However, as we shall show, this problem is much easier to deal with. We shall outline a technique that can be aligned in just a few minutes, using just a simple screwdriver.

In principle, one can treat any optical device as a black box. A collimated beam of light enters one side of the box, and an output beam emerges from the other side of the box. If the output light from the box is not colli-

## Glossary

**Mode field diameter (MFD):** A measure of the intensity profile of light traveling within a fiber. In Gaussian optics, this diameter is measured at the point where the light intensity drops to 13.5% ( $1/e^2$ ) of the peak intensity. In single-mode fibers, it is typically about 15% larger than the actual core size.

**Numerical Aperture (NA):** A measure of the maximum angle at which a given optical system can receive light. If a system can receive light within a cone having a half angle  $q$ , then the NA of that system is equal to  $\sin q$ .

**Extinction Ratio (ER):** A measure of how well an optical beam is polarized. A polarizer is placed in front of an optical beam. The transmitted intensity of the light through the polarizer is measured while rotating the

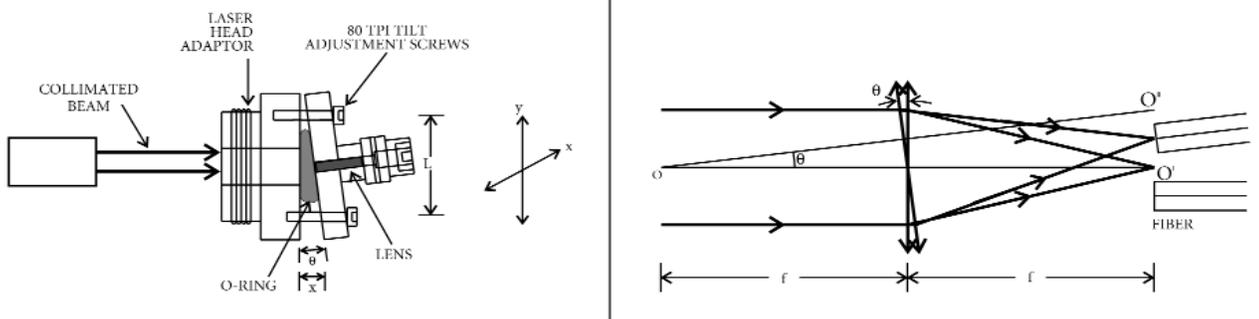


Figure 3. Tilt adjustment operating principle.

mated, then a lens can be added to the output to collimate the light.

Figure 2 shows how two collimators can be used to pig-tail an optical device with optical fibers. First, light from the fiber or optical source is collimated. The collimator is then attached to the input of the optical device. A resilient O-ring is sandwiched between the collimator and the input side of the device. This O-ring acts as a pivot, to align the angular position of the collimated beam with respect to the device. The output fiber is then attached to the output port of the device. The focusing lens is then centered with respect to the collimated beam. This is done by laterally sliding the baseplate containing the focusing optics with respect to the

black box. Next, the tilt axis of the focusing optics is adjusted for maximum coupling efficiency.

The collimating and focusing optics are connected to the black box by three fine thread screws. These screws are adjusted with a screwdriver. By adjusting these screws, one can adjust the tilt angle between the focusing optics and the collimated beam. This in turn moves the point at which the focused spot strikes the fiber. Thus by adjusting the tilt angle, one can align the focused rays to strike the fiber core.

Figure 3 shows the effect of adjusting the tilt angle between the focusing optics and the collimated beam by an angle  $\theta$ . The focused beam is displaced by a distance  $z = f$

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tanq with respect to the fiber, where f is the focal length of the lens being used. For small tilt angles, the resolution of the coupler (Dz) is determined by  $Dz = fDx/L$ , where Dx is the resolution of the screws and L is the length of the lever arm. For 80 TPI screws, a 1-mm focal length lens, and a 20-mm lever arm,

$$Dz = 1 \text{ mm} \cdot 2 \mu\text{m}/20 \text{ mm} = 0.1 \mu\text{m}.$$

This patented technique<sup>1</sup> offers a simple way to assemble hybrid optics systems. It is insensitive to machining and waveguide tolerances, offers submicron resolution, minimal insertion losses, and has been demonstrated to withstand temperature, and humidity cycling, as well as vibration and shock testing.

A useful trick to help in aligning hybrid optics is to use a visible light source to initially align the optics. This makes it easy to track the position of the beam within the optics. A visible source also helps to locate breaks, scattering, and even microbends within hybrid systems.

Another time-saving technique for aligning output fibers in hybrid systems is to initially align the output optics using a multi-mode fiber. Compared to a single-mode fiber, the larger core of a multi-mode fiber is an easier target to find. Once good coupling into the multi-mode fiber has been achieved, replace the multi-mode with single-mode fiber. Only minor adjustments should then be required to optimize alignment with the single-mode fiber.

#### Polarization optics

One issue that we must address is the effect of polarization. Polarizing and polarization maintaining optics are often used in hybrid optical systems. They introduce another set of conditions to the ones already considered. Perhaps the most important factor is the alignment between the polarization axis of the light in free space with the polarization axis of the waveguide. This is particularly important when using polarization maintaining (PM) fibers. For example, assume that we have a perfectly polarized input beam shining into an ideal system, misaligned by an angle q with respect to the slow axis of the PM fiber. The maximum possible value of the output extinction ratio (ER) is thus limited by

$$ER = 10 \log (\tan^2 q).$$

To achieve output extinction ratios greater than 20 dB, the angular misalignment must be less than 6°. For 30 dB extinction ratios, the angular misalignment must be less than 1.8°.

Any stresses or microbends in the optical fibers and connectors, or within the external optical components, can degrade the output polarization. Special termination procedures, stress free glues, and top quality lenses and optics must be used to minimize these stresses, and thus maintain the highest possible extinction ratios.

#### Applications

The range of applications using hybrid optics is almost limitless. The following is just a sample of products.

##### n Fiber optic U-brackets

U-bracket assemblies are designed to transmit light from a fiber across an air gap and back into a second fiber with low losses. A variety of bulk optical devices including polarizers, isolators, filters, and waveplates can be simply inserted and removed from the U-bracket. This makes it ideal for quickly prototyping and test-

ing hybrid systems.

##### n Fiber optic delay lines

Essentially a U-bracket where the length of the air gap can be adjusted, delay lines offer a way to control the distance a signal has to travel, and thus control the time required to travel that distance. Delay lines can be adjusted by as much as 300 mm, with sub-millimeter resolution, corresponding to delay times of 1 ns, with picosecond resolution.

##### n Variable reflector

Fiber reflectors use a fiber collimator together with a mirror. The light from the fiber is first collimated, then reflected back into the fiber. A blocking screw between the fiber and the mirror is used to vary the return signal. The reflection level can be varied from less than 1 dB losses to over 70 dB.

These devices are ideal for testing the sensitivity of components to return losses. This is currently an important issue in long haul transmission systems, as well as CATV networks.

##### n Polarization optics

A new area of growth in telecommunications is in the field of coherent optics. Coherent optical devices use interference and phase information to control signal levels and hence transmit data. However, these optical devices are polarization sensitive. As a result, devices are needed that can either maintain or control polarization within an optical system.

A wide variety of free-space optics are available to control polarization, or to manipulate light based on its polarization state. They include polarizers, waveplates, Faraday rotators, isolators, and polarizing beam splitters. By using these devices in hybrid systems, a whole range of products can be made, including polarized sources, polarization controllers and analyzers, in-line polarizers and isolators, and polarizing or polarization maintaining splitters and combiners. With hybrid optics, one can use different fiber types on the input and output ports. This is very useful when dealing with a combination of regular single-mode fiber and polarization maintaining fiber.

It should be obvious by now that the potential for hybrid optics is almost limitless. With the correct selection of waveguides, lenses, and optics, the number of possible devices is subject only to your imagination.

#### References

1. U.S. Patent Nos. 4,753,510 (June 28, 1988) and 4,889,406 (Dec. 26, 1989); Canadian Patent Nos. 1,258,786, 1,325,122; European Patent Nos. EP 0198657, EP 0348117; Australian Patent Nos., 583911, 621380, 643353; Japanese Patent No. 2,824,489.

**Garland Best is vice president of engineering and Ömür M. Sezerman is president of OZ Optics Ltd., Ontario, Canada.**