THE BELL SYSTEM
TECHNICAL JOURNAL

DEVOTED TO THE SCIENTIFIC AND ENGINEERING
ASPECTS OF ELECTRICAL COMMUNICATION

Volume 62 October 1983 Number 8, Part 1

High-Power Lasers and Optical Waveguides for Robotic Material-Processing Applications

By CHINLON LIN,* G. BENI,* S. HACKWOOD,* and
T. J. BRIDGES*

(Manuscript received April 4, 1983)

For various material-processing applications with robots we propose the use of high-power continuous wave and pulsed lasers (Nd^{3+}:YAG, Argon ion, CO_2, excimer, etc.) and optical waveguides for delivering high powers in the ultraviolet (UV), the visible, and the infrared (IR) regions. We discuss the use of low-loss silica glass fiber waveguides for delivering high-power laser beam in the UV to near-IR spectral region (0.3 to 2 μm), and the use of a waveguiding articulating arm for delivering high-power laser beam in the long IR (2 to 10 μm). We also describe a design for fitting a CO_2 laser waveguiding arm to the robotic arm, as well as the advantages of using optical waveguides for high-power laser delivery to robots for material processing.

I. INTRODUCTION

Optical waveguides are known to be useful for optical signal transmission in which low-power, modulated semiconductor injection laser

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* Bell Laboratories.

light is used for lightwave communication applications.[1] The advent of low-loss optical fiber waveguides, for example, has made possible long-distance, high-bandwidth lightwave communication systems for transmitting audio, data, and video signals. This paper discusses the use of optical waveguides for a different application: *high-power laser transmission* for robotic material-processing applications. Using high-power continuous wave (cw) and pulsed lasers and appropriate optical waveguides for the ultraviolet (UV), the visible, the near infrared (IR), and the longer IR, a robot can manipulate the output beam of a variety of high-power lasers for various processing functions. In Section II we discuss the available flexible waveguides for high-power laser transmission. In Section III we describe a manually operated CO_2 laser waveguiding articulating arm, and in Section IV a design for fitting the waveguiding articulating CO_2 laser arm to a robot arm.

At present, automation of material processing using high-power lasers requires costly, dedicated, large-size equipment. We believe that an inexpensive, small-size robot controlling a high-power laser beam with the help of optical waveguides will make possible many new applications in material processing.

II. HIGH-POWER LASER TRANSMISSION IN OPTICAL FIBER WAVEGUIDES

While the use of high-power lasers for material processing is well known,[2,3] the use of low-loss optical waveguides for high-optical-power transmission is not widely practiced.[4] For robotic applications (applications requiring the unique dexterity and versatility of robots), it is essential that the combination of high-power laser technology and robotics does not reduce the dexterity or flexibility of the robots. The essential element here for providing the flexible link between the high-power lasers (usually heavy and bulky) and the robots is the optical waveguide.

Figure 1 illustrates the basic system schematic for using high-power lasers and optical waveguides in robotic material-processing applications. Depending on the type of high-power lasers, different optical waveguides can be used. For example, in the near-infrared region of 1 to 2 μm, e.g., for high-power Nd:YAG lasers at 1.06 μm, silica glass fibers have excellent transmission characteristics (see Fig. 2). As a result of advances in lightwave communications technology, the loss in a silica fiber waveguide can be very low (~1 dB/km, or 0.01 dB/10 m at 1.06 μm). In this case the loss due to coupling into and out of the fiber waveguide is much larger than the transmission loss for even a 1-km-long optical fiber. Losses in silica glass fibers also can be low enough (for 10 to 100m lengths) for guiding blue-green and red lasers; thus such silica fibers are useful for transmission of high-power Argon

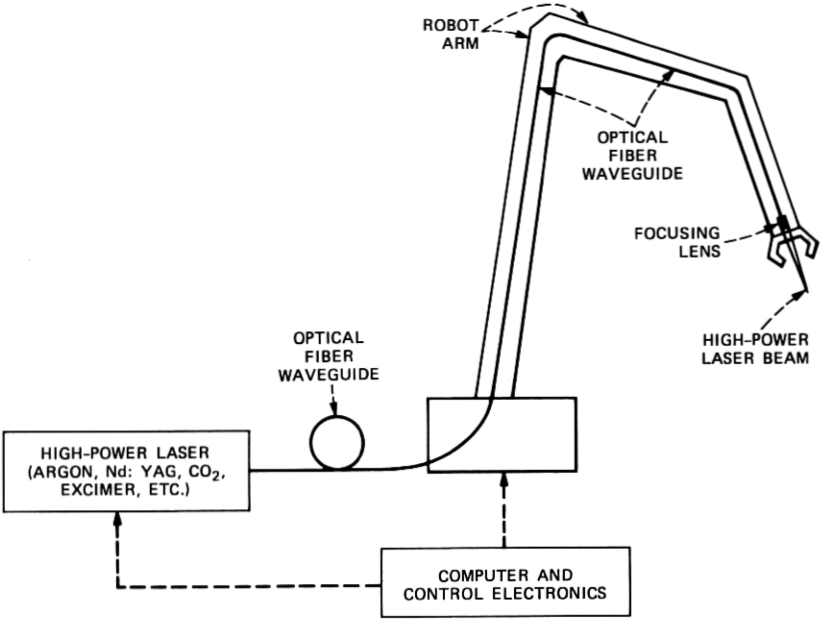

Fig. 1—Schematic of a system using flexible optical fiber waveguides for delivering high-power laser radiation to the robotic arm/hand for various material-processing applications.

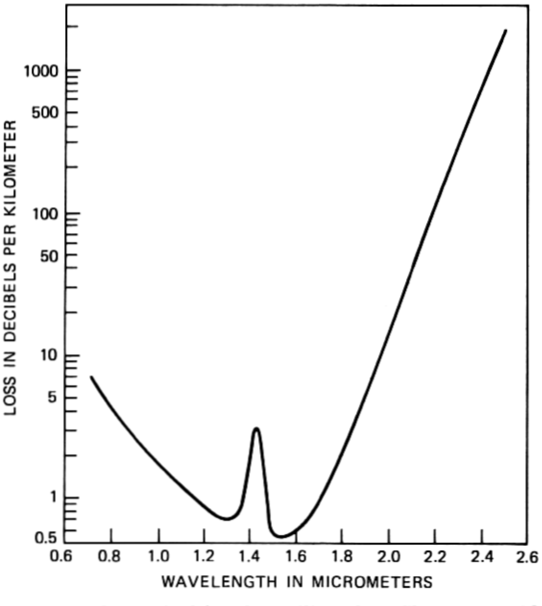

Fig. 2—Loss spectra of a typical low-loss silica glass fiber waveguide. For practical robotic material-processing applications, fiber loss of 1 dB/10 m (or 100 dB/km) could be considered low loss.

ion and Krypton ion lasers, as well as high-power ruby and alexandrite lasers. Recently available special UV silica glass fibers* may also be used for the ultraviolet wavelength region (0.3 to 0.4 μm). The loss is about 1 to 2 dB for every 10m, which is still low. Such fibers are useful for transmitting UV lasers (e.g., He-Cd lasers and excimer lasers) in, for example, photochemical applications.

Thus we have available appropriate optical fiber waveguides for transmitting high-power laser radiation in the spectral region from UV to near IR through at least 5 ~ 10 meters. This allows the bulky high-power laser head and its high-energy power supply (and cooling system, if any) to be separated from the robot, while allowing the powerful laser beam to be delivered to the robot arm or fingertip. As we saw in Fig. 1 a high-power Nd:YAG laser and silica glass fiberguide could be used for guiding the laser radiation to the robot hand (gripper). The silica glass fiber can be routed inside the robotic arm assembly, or mounted externally but attached to the side of the arm, depending on the situation or work requirement. The output fiber end can have a microlens (such as a half-pitch graded-index-rod lens) or a small conventional lens attached for output beam focusing.

For transmitting Nd:YAG lasers, ruby lasers, Argon ion lasers (in the visible and the near-infrared spectral region), the silica glass fibers are typically very small in dimension: outer diameters are on the order of a few hundred micrometers to a few millimeters, including the protecting jacket or cable. For high-laser-power output with well-defined spatial distribution (e.g., for maximum brightness, or best focusing), single-mode fibers with appropriate refractive index difference Δn and core diameter 2a can be designed (with normalized frequency $V \leqslant 2.4$ at the laser wavelength) for use in these different wavelength regions. If maximum overall energy transmission without concern for the spatial quality of the laser beam output is desired, a large-core, high numerical aperture (N.A.) silica glass fiber can be used for high-energy delivery to the robot. For the propagation properties and design considerations in single-mode and multimode silica glass fibers, appropriate references[1] should be consulted.

For transmitting high-power, longer infrared (2 to 10 μm) lasers such as CO_2 lasers, a configuration similar to that shown in Fig. 1 can be used, if a truly flexible CO_2 laser fiberguide is available. Presently, various glass and crystal fibers are being developed for this spectral region.[5] Notably among them are the polycrystalline KRS-5 fibers[6] and the single-crystal AgBr fibers[7] for CO_2 lasers transmission. However, presently available long infrared fibers tend to be very lossy and

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* UV fibers with losses in the 150 dB/km range for $\lambda \sim 310$ nm range have been reported by, for example, Quartz and Silice, France.

fragile. Thus the mechanical and optical properties are not yet truly satisfactory. Therefore, at present, bulky conventional articulating arms (consisting of aligned mirrors) are used for most applications requiring some flexibility in CO_2 laser delivery. To improve the flexibility and stability, Bridges and Strnad have developed a novel "waveguiding" articulating arm for transmitting high-power CO_2 laser radiation.[8] The arm, shown in Fig. 3, has been designed for manual control. It is compact and relatively articulate. In the future, truly

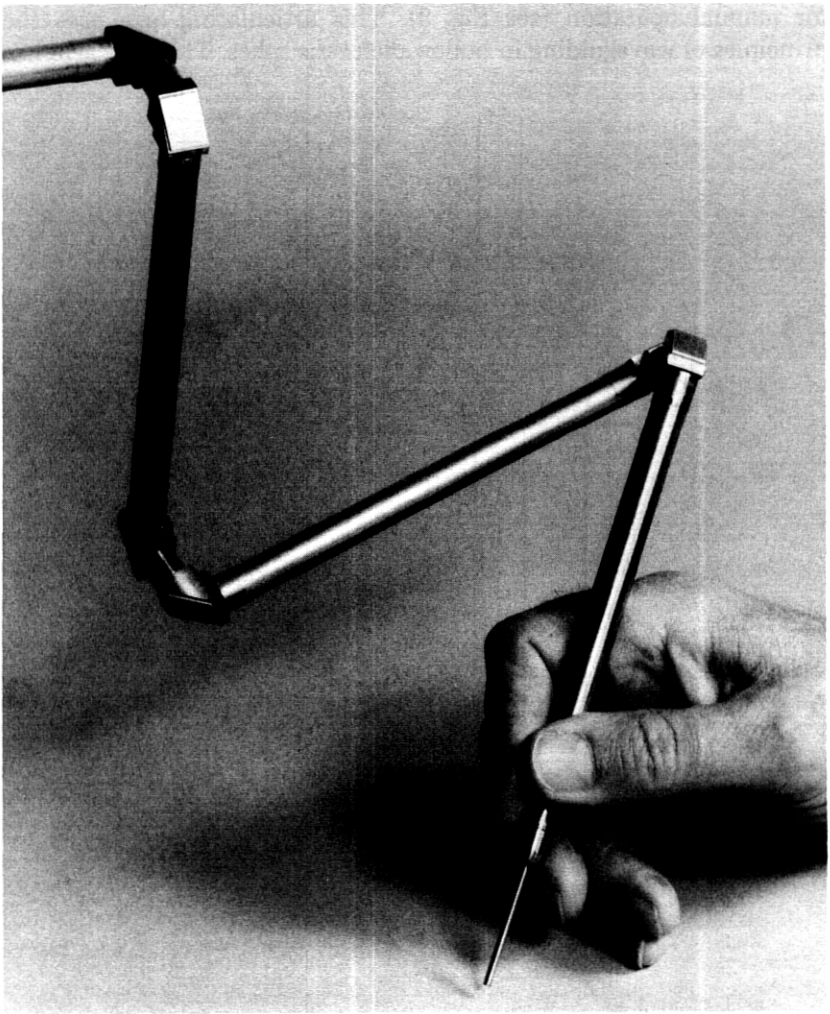

Fig. 3—The Bridges/Strnad waveguiding articulating arm for high-power CO_2 laser delivery.

flexible long-wavelength fibers are expected to have lower loss and higher strength than those presently available. Until then, the Bridges/Strnad waveguiding articulating arm would be the choice for CO_2 laser delivery to the robot. In Section III we discuss in more detail the design of this CO_2 laser arm; in Section IV we describe designing this laser arm to fit onto a robot arm for material processing.

III. BRIDGES/STRNAD WAVEGUIDING ARTICULATING ARM FOR LONG-IR LASER RADIATION

Figure 4 shows the design details of the Bridges/Strnad arm used for manual operation (see Fig. 3). This articulating arm uses the principles of waveguiding in hollow dielectric tubes. This new arm has

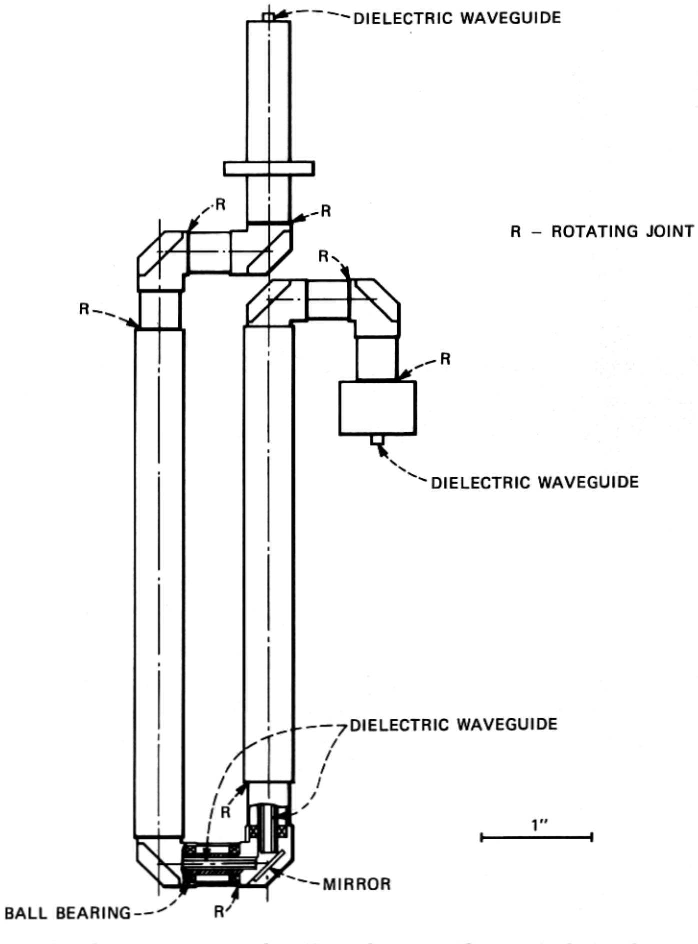

Fig. 4—The design of the Bridges/Strnad waveguiding articulating laser arm for flexible delivery of high-power, long-IR (e.g., CO_2 laser at 10.6 μm) optical radiation.

a number of advantages over previous articulating arms, including compactness and better pointing accuracy when compared with conventional articulating arms.[9] Flexible waveguides such as metal waveguides[10] and presently available infrared fibers are problematic because of the multimode nature of the guide. Single-mode radiation from the laser is rapidly degraded into a multiple-mode pattern that changes in form as the guide is moved. The degradation reduces considerably the maximum intensity that can be obtained by focusing the output radiation. In the case of articulating arms of conventional design the single mode is preserved, but unless the input beam is launched precisely on axis and the mechanism of the arm is precisely correct, the output beam will wander in a complicated manner as the arm is manipulated. Such arms are also characteristically large and cumbersome. The Bridges/Strnad arm design avoids this problem by propagating the radiation in straight, hollow, dielectric waveguides of the Marcatili-Schmeltzer type.[11] A single mode can be maintained in the guide, while the pointing accuracy is far less affected by initial launch conditions and accuracy of construction. (Pointing accuracy is determined by how closely the direction of the output beam conforms to the mechanical axis of the arm.) A further advantage is the compact design resulting from the elimination of diffraction spreading of the beam, by the guiding action of the waveguide.

The Marcatili-Schmeltzer waveguide carries radiation in the hollow circular bore of a dielectric tube. The dielectric need not be transparent to the radiation being guided. The mechanism of guiding can be thought of as a continual-glancing-angle Fresnel reflection from the dielectric walls. This reflection is not total, but close to 100 percent for very shallow incident angles to the walls. The modes of propagation have been calculated by Marcatili and Schmeltzer,[11] and they find that the lowest loss mode is the EH_{11} mode. An appropriate waveguide size is 50 to 200 wavelengths in diameter. This size is large enough to give low loss, but still retain adequate guiding so that straightness of the tube is not an important factor, although curvature of the tube axis introduces extra loss by an amount that increases with tube diameter.

Since the dielectric need not be transparent to the radiation, glass or quartz tubing which is readily obtainable in precision bore form can be used to transport 10.6-μm radiation. Single-mode laser radiation is conveniently launched into the waveguide by means of a lens (Fig. 5). The focal length of the lens is chosen to closely match the input Gaussian beam to the guided beam with small loss.[12] Short gaps in the tube can be tolerated with small loss so that mirrors which turn the beam through a 90-degree angle and are basic to the operation of the infrared articulating arm can be used in a simple arrangement (see Fig. 4).

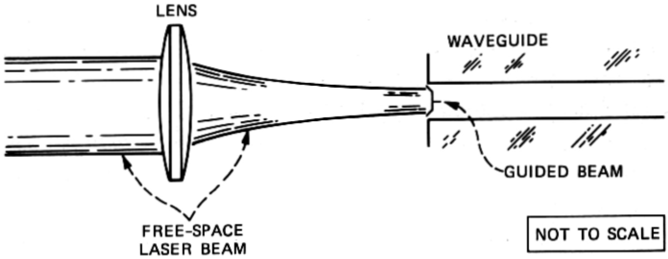

Fig. 5—Launching a free-space Gaussian beam into waveguide by means of a lens.

As a secondary feature, the glass or other visibly transparent waveguide tube can act as a light pipe to carry visible light through the arm. This light can be used for illuminating the work area, or for aiming the output beam. For this application the mirrors should be highly reflective in the visible as well as the infrared range. A suitable material is evaporated silver.

With the above concept in mind, various components of a possible waveguide articulating arm were tested in the laboratory, using a 10-μm CO_2 laser as a source. A 13.9-cm length of fused quartz tubing with 1.55-mm bore was tested. When a 30-cm focal length lens was used to focus the radiation into the guide, a transmission of 93 percent was found. To test the effect of small misalignments, the tube was pivoted off axis around the input point by one-half of one degree, and the transmission dropped by only 2 percent. Finally, a mock-up of a corner elbow (see Fig. 4) was made on the bench and a transmission of 95 percent was measured. This information demonstrated the feasibility of the idea and a complete arm was designed and fabricated (see Fig. 3). The arm contains three sections of waveguide that are 13 cm long and three more that are 2 cm long. The six corner mirrors used were commercially obtained. They were made from silicon 1 mm thick and were coated with silver and a transparent protective layer. The corners swivel on precision ball bearings. With a total length of 40 cm the arm can access any point in a 80-cm-diameter sphere. The completed arm was tested and found to have a transmission of 80 percent. Power up to 5W cw was transmitted with no damage. The 1.55-mm diameter beam from the output tube was substantially single mode and could be focused to a near-diffraction limited spot. As we expected, there was no wander of the output beam relative to the output tube as the arm was moved. The small size and light weight made it very easy to manipulate the arm and to place the output beam in any desired position.

IV. A ROBOTIC ARM FITTED WITH THE WAVEGUIDING ARTICULATING CO_2 LASER ARM

The simplistic approach to using the Bridges/Strnad waveguiding CO_2 laser arm is to make the robot gripper hold and maneuver the tip of the articulating laser waveguide. This approach, however, has a major drawback. Reorientation of the laser-beam output requires, in general, rotations of all five revolute joints of the articulated waveguide. In many cases, this complex reconfiguration of the articulated waveguide prevents a continuous rotation of the laser-output tip and requires the robot to follow a complicated path.

In addition, a force and torque sensor on the gripper would be essential to ensure that the articulated waveguide is not damaged by the robot in the attempt of imposing a particular five-link configuration. This is still beyond state of the art robotics, since even the turning of a simple two-link crank by a robot arm is a complex compliance problem not yet satisfactorily solved.

A second approach is to fit the waveguide within or beside the robot. Because of the required 90-degree revolute joint articulations, this is not a trivial task. In fact, many existing robots have prismatic joints and/or unsuitable dimensions.

We now propose a new robot system consisting of two arms: master and slave. The master arm is positioned by motors, whereas the slave arm only carries the waveguide. The slave arm is the Bridges-Strnad-type five-link waveguiding laser arm with 90-degree rotational joints. Unlike the original Bridges-Strnad arm shown in Fig. 2, it now has nine (rather than six) mirrors and a different link geometry as described below. The master arm is, for example, a Microbot Alpha* whose hand gripper and side casing have been removed. The robot has a repeatability of $\sim 250\ \mu m$ and a positioning speed of 50 cm/s. The two arms are connected "in parallel" as follows.

Figure 6 shows schematically the connection between the master and the slave arms. The mirrors of the slave arm are labeled 'b' to 'j'. Laser input and output are at 'a' and 'k', respectively. Five mirrors are rigid and four ('b', 'e', 'g', and 'h') are movable. The axes of rotation of the master arm are indicated by rotation angles θ_1 to θ_5. Except for axis 5, the axes of rotation of the slave arm coincide with the corresponding axes of rotation of the master arm. For example, a rotation θ_3 of the master arm corresponds to an equal angle rotation of the slave arm about the direction 'f'–'g'. The slave arm direction 'i'–'j' does not coincide with, but is parallel to, θ_5 of the master arm. The connection between these two axes is through a pair of identical gears, as shown in Fig. 7. The connection between the two arms at the other

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* New industrial-quality product of Microbot, Inc.

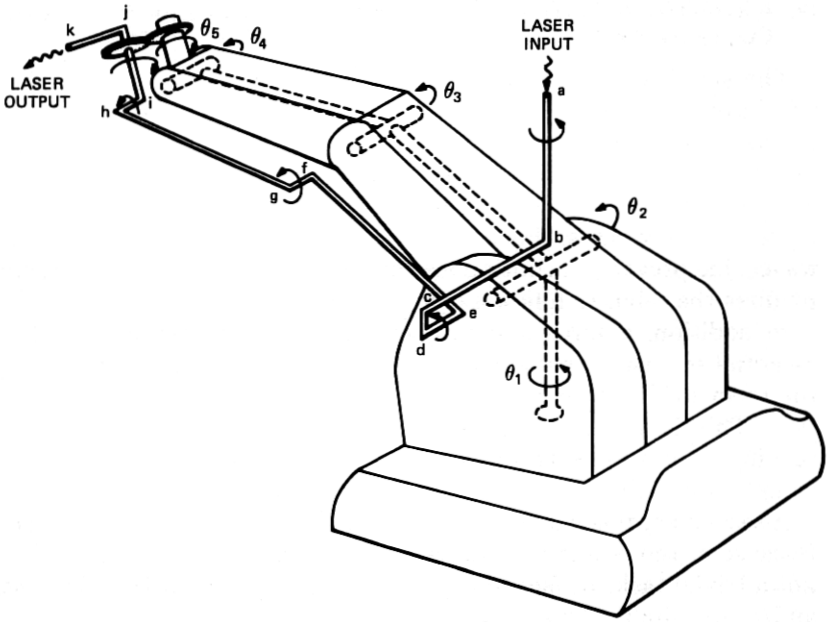

Fig. 6—Schematic diagram showing the master slave configuration of the CO_2 laser beam positioning robot.

four axes of rotation is via rigid mounts (not shown in Fig. 6) except for axis 3, where a moderately compliant plastic mount is used for attaching the two arms. This connection compensates for possible slight misalignments between the first four pairs of axes and thus prevents damage to the slave arm.

A precise description of the two-arm assembly is conveniently done using Denavit-Hartenberg[13] notation, which is standard for robots. The five links of the slave arm are defined as follows. The origin is at the intersection between axes θ_1 and θ_2. Link 1 is segment 'bcde'; Link 2 is segment 'defg'; Link 3 is segment 'fghi'; Link 4 is segment 'hij'; and Link 5 is segment 'ijk'. The exact geometry is given in Table I, where α_i is the twist angle, a_i is the ith link length, and d_i is the (i-1) to ith link distance. These definitions correspond to the conditions: 1) $a_2 = a_3 =$ '*hg*' = '*ef*'; 2) '*hi*' = '*gf*' = '*de*' = $2d_4$; 3) '*ab*' '*cd*', '*ij*', '*jk*' have arbitrary length.

The transmitted power efficiency should remain high. Extrapolating from the 6-mirror configuration, approximately 70-percent efficiency is expected. The resolution is determined by the master arm. In our case it is approximately 250 μm. Note that the slave arm is detachable so that the robot can be used for other tasks.

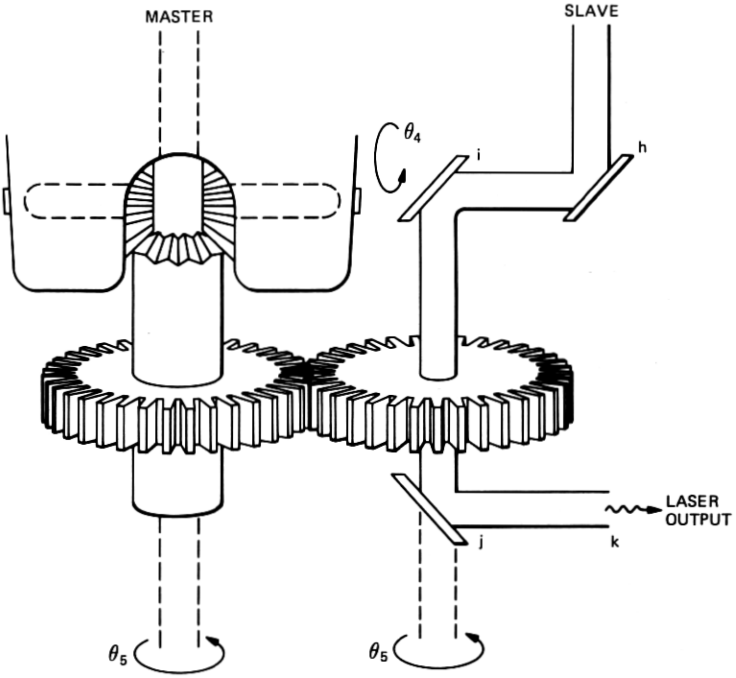

Fig. 7—Detail of the gear-connection of the 4th and 5th revolute axes of the master arm with the 'h-i' and 'i-j' revolute axes of the slave arm.

Table I—Denavit-Hartenberg manipulator parameters for the two-arm robot system

Link	Master			Slave		
	Twist Angle, α_i, in degrees	Link Length, a_i, in cm	Link Distance, d_i, in cm	Twist Angle, α_i, in degrees	Link Length, a_i, in cm	Link Distance, d_i, in cm
1	−90	0	0	−90	0	10.0
2	0	17.78	0	0	17.78	0
3	0	17.78	0	0	17.78	0
4	+90	0	0	+90	0	1.27
5	0	0	0	0	0	0

V. ROBOTIC MATERIAL PROCESSING

The use of high-power Nd:YAG lasers and CO_2 lasers for material processing such as welding, cutting, drilling, scribing, trimming, heat treating, annealing, etc., are well-documented.[2] Thermally and photochemically induced reactions are also well known. The advantages of robot-laser-processing of materials are dexterity in robotic-laser-beam maneuvering, processing of complex-shaped materials, and versatility in adapting the changing environments and changing material-processing functions. Existing nonrobotic, dedicated laser material processing apparatus[2,3] is much more restricted and expensive to modify should work requirement change. The combination of robots and high-power lasers is a natural technological direction to pursue for more versatile material handling and processing. The various forms of optical waveguides we describe here provide the important, and maybe indispensible, flexible links between robots and high-power lasers.

The use of these flexible, lightweight optical fiber waveguides (assuming they will also be available at long IR in the near future) for delivering high-power laser radiation to robots for material processing has several distinct advantages:

1. The bulky, heavy laser system could be remotely located so that any high electromagnetic interference (noise interfering with computer signal control of the robot and data transmission) could be eliminated.
2. The use of lightweight flexible optical fiber waveguides on the robot arm (or body) allows laser-material processing in mobile robots without undue constraints on their mobility.
3. Since the work space is not crowded by the use of high-power lasers, multiple robots can work together simultaneously in a complicated laser-material-processing task.
4. The use of several different kinds of high-power lasers at different wavelengths in a single robot can be achieved easily by routing multiple waveguides of different types through the robot, with appropriate shutters to control the switching of laser beams.

Our preliminary experimental results show that we can transmit (deliver) 5W of cw Nd:YAG laser power to the silica glass fiber output suitable for laser soldering. With high-power Nd:YAG lasers and more effort in fiber design and coupling, we expect to be able to deliver more than 10W (cw) through single-mode fibers and more than 25W (cw) through multimode, large-core silica glass fibers. Since the damage threshold for silica glass fibers is in the GW/cm^2 range, pulsed laser of high peak power also can be transmitted. With such lightweight optical fibers giving out such high-output laser power at the fingertip (gripper) of a robot, even a small inexpensive robot can perform many complicated material-processing or microprocessing functions.

With long IR lasers such as CO_2 lasers and the Bridges/Strnad type waveguiding articulating arm, 5W of power has been transmitted. Much higher-power (20 to 100W) transmission is expected before mirror damage occurs. With future advances in low-loss long IR fibers, truly flexible CO_2 laser transmission at 20- to 40W levels[6] can be expected.

The positioning resolution and repeatability in robotic laser material processing depend on the specific robot design. High positioning precision (10-μm repeatability) and high positioning speed (1.6-m/s) robots[14] are fast becoming available. The use of lightweight flexible waveguides for high-power laser delivery to robot arm ensures that such high positioning accuracy and speed will not be compromised. This is another distinct, significant advantage.

In summary, the use of appropriate optical waveguides for transmitting and delivering high-power laser radiation to a robot arm will make possible complex robotic-laser-processing of materials. Medical and biological applications of robotic microprocessing with fiber-guided lasers can also be envisioned. These could be considered a special case of robotic material processing. The combination of technology of high-power lasers, optical waveguides, and robotics will certainly open up a new era of laser material processing.

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AUTHORS

Chinlon Lin, B.S.E.E., 1967, National Taiwan University; M.S., 1970, University of Illinois; Ph.D., 1973, University of California at Berkeley; Bell Laboratories, 1974—. Mr. Lin has worked on tunable dye lasers, short-pulse generation, nonlinear optics in fibers for frequency conversion, single-mode fiber dispersion and bandwidth studies, picosecond-injection-laser pulse generation, and high-speed optoelectronics. At Berkeley, he received an IBM

Fellowship and a Lankersheim Scholarship. He is currently in the Laser Science Research Department. Mr. Lin received an IEE (London) Electronics Letters Premium Paper Award in 1980 for a paper on zero-dispersion-wavelength tailoring in single-mode fibers. Senior Member, IEEE, Topical Advisor for Fiber and Integrated Optics for the Optical Society of America since 1982.

Gerado Beni, Laurea (Physics), 1970, University of Florence (Italy); Ph.D. (Physics), 1974, University of California, Los Angeles; Bell Laboratories, 1974—. Mr. Beni has been involved in research with Bell Labs, first at Murray Hill as a Resident Physicist in the Scattering & Low Energy Physics Department (1974–76), and as MTS in the Theoretical Physics Department (1976); at Holmdel he was a member of the Solid State Device Physics Department (1977–82), and currently is in the Robotics Systems Research Department. His expertise includes four major fields: theoretics, electrochemistry, displays, and robotics. In these fields he has contributed approximately 80 papers and 8 patents. Fellow, American Physics Society; Member, New York Academy of Science, the Electrochemical Society, SID, and Robotics International.

Susan Hackwood, Ph.D., 1979 (Solid State Electrochemistry), Leicester Polytechnic, United Kingdom; Bell Laboratories, 1980—. Ms. Hackwood has conducted research in catalysis, display technology, physical electrochemistry, sensors, and device robotics. Currently in the Electronics Research laboratory, she is involved with device robotics research for semiconductor fabrication. She has contributed approximately 40 technical papers and holds eight patents in the fields of physical electrochemistry, displays, and robotics. She is on the steering committee for Display Technology (ECS), which now includes robot sensors, and is the robotics representative of the Electronic Materials Committee of the Metallurgical Society of AIME. Member, American Physical Society, The Electrochemical Society, SID, and Robotics International.

Thomas J. Bridges, B.Sc. (Engineering), 1943, London University; Royal Naval Scientific Service (U. K.), 1944–1956, 1959–1963; Bell Laboratories, 1956–1958, 1963—; Massachusetts Institute of Technology, 1967–1968. At MIT Mr. Bridges was a Visiting Professor of Electrical Engineering. At Bell Laboratories he has worked on millimeter waves, microwaves, infrared lasers, and optically pumped far-infrared lasers. He currently supervises a group working on vapor phase epitaxy of semiconductor compounds.