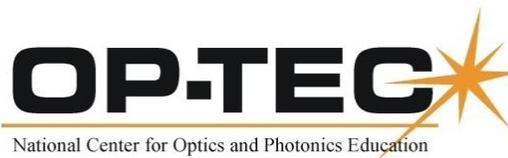

Fiber Laser Applications

OPTECS AND PHOTONICS SERIES

**OP-TEC: The National Center of Optics
and Photonics Education**

An NSF ATE Project



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This document was developed by OP-TEC: The National Center for Optics and Photonics Education, and initiative of the Advanced Technological Education (ATE) program of the National Science Foundation.

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PREFACE

This module addresses the basic concepts underlying the operation of fiber lasers. It supplements the fiber laser material presented in OP-TEC's *Elements of Photonics Course* by providing a more up to date and detailed description of how these lasers are used in industry. Other modules that supplement this course can be found in *OP-TEC's Enabled Technologies* series. This series provides instructional materials for several photonics enabled technology areas, as listed below. (This list will expand as the OP-TEC series grows. For the most up-to-date list of the OP-TEC modules, visit <http://www.op-tec.org>).

Manufacturing

Laser Welding and Surface Treatment

Laser Material Removal: Drilling, Cutting, and Marking

Laser in Testing Measurement: Alignment Profiling and Position Sensing

Laser in Testing and Measurement: Interferometric Methods and Nondestructive Testing

Environmental Monitoring

Basics of Spectroscopy

Spectroscopy and Remote Sensing

Spectroscopy and Pollution Monitoring

Biomedicine

Lasers in Medicine and Surgery

Therapeutic Applications of Lasers

Diagnostic Applications of Lasers

Forensic Science and Homeland Security

Lasers in Forensic Science and Homeland Security

Infrared Systems for Homeland Security

Imaging System Performance for Homeland Security Applications

Optoelectronics

Photonics in Nanotechnology

Photonics Principles in Photovoltaic Cell Technology

The modules pertaining to each technology can be used collectively as a unit or separately as stand-alone items, as long as prerequisites have been met.

For students who may need assistance with or review of relevant mathematics concepts, a review and study guide entitled *Mathematics for Photonics Education* (available from CORD) is highly recommended.

The original manuscript of this module was prepared by John Ready and Feng Zhou and edited by John Souders (OP-TEC).

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Fiber Laser Applications

INTRODUCTION

Although fiber lasers are a relatively new type of laser, they have begun to compete for applications with many other types of lasers having active materials such as solid rods, gases or semiconductors. Many of these other lasers have reached a state of relative maturity. However, the applications of fiber lasers are still in a state of rapid development but already have become important in materials processing, communications, spectroscopy, medicine and the military. This module will describe the practical applications of fiber lasers and how fiber lasers offer advantages over other types of lasers, such as high efficiency, long lifetime, low maintenance and small size.

REQUIREMENTS

Before beginning this module, students should have completed the companion module, “Fiber Laser Basics”. Also, before beginning the laboratory exercises, students should have training in laser safety.

BASIC CONCEPTS

Introduction to Fiber Laser Applications

Although they are still fairly new and are still developing, fiber lasers already have many established applications and are being investigated for many others. This module will describe a variety of these applications. We begin with a brief discussion on more established lasers for reference purposes. The module then describes the advantages that fiber lasers offer. It continues with a discussion of fiber laser applications in material processing, which is now its best established use. The module concludes with a variety of other applications in such areas as communications, spectroscopy, medical technology and the military.

Established Laser Types

A variety of laser types have been developed since the original ruby laser was invented in 1960. Many of these lasers have become mature and well established for many applications. Because the widest application of fiber lasers has been in materials processing (welding, cutting, etc.), we start with the lasers that have been commonly used in this area. They are listed in Table 1.

Table 1. Established lasers used in materials processing

| Lasers | Wavelength Micrometers | Power (W) |
|-------------------------------------|------------------------|------------------|
| Repetitively pulsed Nd:YAG | 1.06 (peak) | 150,000 |
| CW Nd:YAG | 1.06 | up to 5000 |
| Repetitively pulsed CO ₂ | 10.6 | > 1000 (average) |
| CW CO ₂ | 10.6 | up to 30000 |
| CW laser diode stack | 0.9-0.98 | up to 10000 |
| CW disk laser | 1.03 | Up to 16000 |

The values given in the table for power are not the highest ever achieved but represent what is commercially available. The values are for multimode operation; the single-mode values are lower. Also, the values of power for pulsed lasers are for pulses with duration in the millisecond regime, since these durations are most often used in materials processing. Other shorter pulses are available and may be used in other applications.

CO₂ lasers, Nd:YAG lasers, semiconductor diode lasers and disk lasers use very different materials as lasing media. CO₂ lasers are gas lasers that use CO₂ as the lasing medium. A gas mixture containing CO₂ is excited by an electrical discharge through the gas. Nd:YAG lasers are solid-state lasers that use the rare earth element neodymium implanted in a crystal of yttrium-aluminum-garnet (YAG) as the lasing medium. They are excited optically by light from flashlamps, arc lamps or laser diodes. Semiconductor diode lasers are p-n junctions in semiconductor materials, like aluminum gallium arsenide, and are electrically excited. In order to produce high values of output power, many diode lasers are fabricated in a bar and then bars are arranged in stacks. Disk lasers use a thin disk of a solid state active material, often ytterbium doped YAG (Yb:YAG), which usually emits in the near infrared. The disk is in close contact with a heat sink. It is pumped from the side by semiconductor diode lasers.

CO₂ lasers emit at an infrared wavelength of 10.6 micrometers. Nd:YAG, semiconductor diode lasers and disk lasers emit in the near infrared near 1 micrometer. Because of these different wavelengths, some materials are better absorbers for the different laser beams. Most metals are reflective at wavelengths near 10 micrometers. Thus, it requires more power to melt or vaporize metals with a CO₂ laser than with any of the other shorter wavelength types. Still because of the higher power available, CO₂ lasers can be very effective for welding or cutting metal.

The different lasers produce different beam shapes. The beam divergence angle θ is given approximately by the equation:

$$\theta = \lambda/d \quad \text{Equation 1}$$

Where λ is the wavelength and d is the diameter of the aperture from which the beam emerges. Since the wavelength and diameter are in the same units, the beam divergence angle is in radians. Because the wavelength of the carbon dioxide laser is about 10 times larger than that of the other types of lasers, the beam divergence angle is larger. This is partially compensated

by the fact that the exit aperture of the CO₂ laser can be made larger. Conversely, the exit aperture of a semiconductor laser diode is very small so that its beam divergence angle will be large. This must be corrected by the use of optics. The beam divergence angle of the Nd:YAG laser and the disk laser are similar and are smaller than those of the carbon dioxide and semiconductor lasers.

Advantages of Fiber Lasers

As compared to other competing lasers, fiber lasers can offer many advantages.

High Efficiency

Fiber lasers offer higher efficiency than other lasers used for similar applications, like the Nd:YAG laser and the carbon dioxide laser. The efficiency is the fraction of the electrical power input that emerges as laser power output. For Nd:YAG lasers the efficiency is around 2%. For carbon dioxide lasers, it is often in the 15-20 % range. For fiber lasers it is usually in the 25 -30% range. Also there is less energy needed for purposes other than pumping the laser, like cooling and circulating gas.

Power

Because fiber lasers can be coiled easily within a small volume, they can have great length, up to kilometers. This fact allows the power output to be scaled upwards in a simple manner. Fiber lasers have been developed with CW output power up to many kilowatts. In single mode operation, CW operation up to 10 kW has been demonstrated. In CW multimode operation, 50 kW has been obtained. In pulsed operation, megawatt values of peak power are possible.

High Brightness

Brightness (power per unit area per unit solid angle, also called radiance) can be very high in a single mode fiber laser. Brightness is usually given in units of watts per square centimeter per steradian, where a steradian is a unit of measurement of solid angles. Irradiance (power per unit area at a surface, also called intensity) is another commonly used term to describe laser brightness..

The area of the beam as it emerges from the fiber is that of the fiber core, which is small and in single transverse mode operation, the angular spread of the beam is at a minimum. This means that the brightness is very high.

EXAMPLE 1

In a single mode fiber laser emitting 100 watts CW and with a core having 50 micrometer diameter, the power per unit area at the end of the core is given by

$$P = 100W / \left(\frac{\pi(50 \times 10^{-4})^2}{4} \right)$$
$$P = 5.1 \text{ megawatts/cm}^2$$

According to Equation 1, the beam divergence angle is:

$$\theta = \frac{\lambda}{d} = \frac{1070 \times 10^{-7}}{50 \times 10^{-4}} = .024 \text{ radians}$$

The solid angle is

$$\Omega = 4\pi\theta^2 = 4\pi(.0214)^2 = .00575 \text{ steradians}$$

The brightness is

$$L = \frac{P}{\Omega} = \frac{5.1 \frac{\text{megawatts}}{\text{cm}^2}}{.00575 \text{ steradians}} = 887 \frac{\text{megawatts}}{\text{cm}^2 \text{ steradians}}$$

When the beam emerges from the fiber, it may be easily collected with a lens and focused to a very small spot. With the high brightness, this yields very high irradiance at the surface of a work piece, a factor important for materials processing.

Excellent Beam Quality

In laser science, a parameter defining the quality of the laser beam is denoted M^2 . This parameter is defined as the ratio of the divergence angle of the beam to the beam divergence angle of the lowest spatial mode (the Gaussian mode) with the same aperture located at the same position. For a pure Gaussian beam, this ratio is obviously unity. If there is a small mixture of higher order modes, the value of M^2 will be slightly greater than unity and if there are many high order modes in the beam, the value of this parameter will be much greater than unity.

Fiber lasers operating at relatively low power generally have small values of M^2 , often less than 1.1. This means that the quality of the beam is excellent. In general, as the power of the laser increases, the value of the beam quality factor also increases. But because of the nature of the fiber laser, with the beam generated in a fiber, the increase in M^2 with power is less than it is in most other lasers. Single mode fiber lasers have been fabricated with values of M^2 remaining near unity at fairly high values of power.

Beam quality is important for many applications. In fiber-optic communications, beams must have M^2 close to 1 in order to be coupled to a single-mode optical fiber. In laser materials processing, small values of M^2 are required in order to focus the beam to a small spot. This gives fiber laser lasers an advantage over other lasers for these applications.

Low Operating Cost

Because higher efficiency leads to less use of electricity and because there is little maintenance required and no use of gas in the laser, the operating cost of fiber lasers is lower than that of competing lasers. According to one estimate, at the 4 kW level, the operating cost for a fiber laser is about \$12 per hour for 8 years of use. This estimate includes electricity, maintenance, replacement parts, gas, and depreciation and interest on the original purchase. In comparison, under the same conditions the operating cost for CO₂ lasers was estimated to be about \$24 per hour and about \$38 per hour for Nd:YAG lasers.

Low Maintenance

There are no periodic maintenance tasks to be performed. There is no mirror adjustment or replacement and no regular pump source replacement. There are no blowers or gas supplies and there are no moving parts. In contrast to competing lasers, like carbon dioxide and Nd:YAG for materials processing applications, fiber lasers do not require preventative maintenance. Output optics and coolant may need to be properly serviced by the user, but otherwise a fiber laser will perform consistently without adjustment or other servicing. These low maintenance requirements are one important factor in the low operating costs mentioned above.

Long Lifetime

The operating lifetime is determined for fiber lasers by the lifetime of the diode laser pumps, which is estimated to be 100,000 hours. This is much greater than for Nd:YAG lasers and carbon dioxide lasers.

Reliability

The manufacturers of commercial fiber lasers claim very high reliability for their products. Their claim is that fiber lasers will operate continuously, 24 hours per day, for decades. This claim is based on the simplicity of fiber lasers and on the fact that they have no components that degrade or require periodic maintenance.

Easy Coupling into Fibers

Because the beam emerges from the end of the core of a fiber, it is very easy to direct it into the end of another fiber. Simple bonding or end-to-end compression, well known techniques, can be used.

Compact Size

Fiber lasers can be contained in very small spaces. For example, one commercial ytterbium fiber model emitting 100 W, capable of welding and cutting, is contained in a rack mount 66 X 44.8 X 26.6 cm. This is much smaller than would be possible with a CO₂ or Nd:YAG laser. Thus, for applications such as materials processing, use of a fiber laser can save valuable factory floor space reducing the amount of area that needs to be heated, cooled and rented.

Future Prospects

Fiber laser capabilities are expected to continue to advance, with commercially available power levels reaching 100 kW or more. The beam quality should continue to improve and the power levels available in single mode operation should also increase. The output power available at the wavelength of 1.54 micrometers, useful for telecommunications, will increase to the kilowatt level. The cost for fiber lasers is expected to decline further, making them even more competitive with other lasers. In summary, these advances will help expand the applications of fiber lasers to more industries.

Applications in Materials

Materials processing is the area that has become the most developed application for fiber lasers. This has included welding, cutting, micromachining, marking and engraving, and wafer processing.

Welding

Welding applications may be performed in two different ways, conduction welding and penetration welding.

Conduction Welding

Conduction welding is performed by delivering the laser beam to a small area on the surface of the work piece. The laser energy is absorbed at the surface. The energy heats the surface to a high temperature so that a thin layer near the surface is melted. Energy is carried into the interior of the material by thermal conduction. This in turn melts the material to some depth. The depth z to which the energy penetrates in time t is given approximately by:

$$z^2 = 4\kappa t \quad \text{Equation 2}$$

where κ is the thermal diffusivity of the material. Thermal diffusivity is a material parameter which has dimensions of cm²/sec and describes how thermal energy diffuses through a material. The higher the value of thermal diffusivity, the greater the depth that can be melted in a given time.

EXAMPLE 2

The depth of energy penetration for a 10 millisecond laser pulse striking a stainless steel surface can be calculated using Equation 2:

$$z^2 = 4\kappa t \quad \kappa \text{ for stainless steel is } .04 \text{ cm}^2/\text{sec}$$

$$z^2 = 4 (.04 \text{ cm}^2/\text{sec})(.010 \text{ sec}) = .0016 \text{ cm}^2$$

$$z = .04 \text{ cm}$$

Thus, conduction welding is limited to relatively thin material samples.

The earliest uses of lasers for welding involved conduction welding and were carried out with pulsed lasers or with continuous lasers having power below the 1000-1500 watt range. Very early in the history of lasers it was demonstrated that conduction welding could produce high quality welds with small heat-affected zones and with full strength (that is tensile strength as high as that of the original material).

Penetration Welding

In a different welding procedure, called penetration welding, the laser delivers higher irradiance to the surface. The beam vaporizes some material, produces a hole in the material and energy is delivered to the bottom of the hole. This requires an irradiance of around 10^6 watts/cm². In penetration welding the energy is delivered throughout the depth of the material. Thus, the depth is not limited by thermal conduction from the surface, and it is possible to weld to much greater depths. Penetration welding is also sometimes called deep penetration welding or keyhole welding. Usually multi-kilowatt lasers are used for penetration welding. Fiber lasers have been used for both conduction welding and for penetration welding.

Welding Results

The use of fiber lasers is effective in welding applications. This has been demonstrated in many published papers and some applications described in these papers have been transferred to production. Most of the welding applications of fiber lasers have involved ytterbium-doped fibers operating near 1070 nm, because these lasers can emit the highest values of power. Figure 1 shows a typical arrangement for welding applications. The mirrors for the fiber laser are shown as distributed Bragg reflectors, which were described in the companion module. The figure also shows the beam transmitted through a transmitting fiber to a remote work piece.

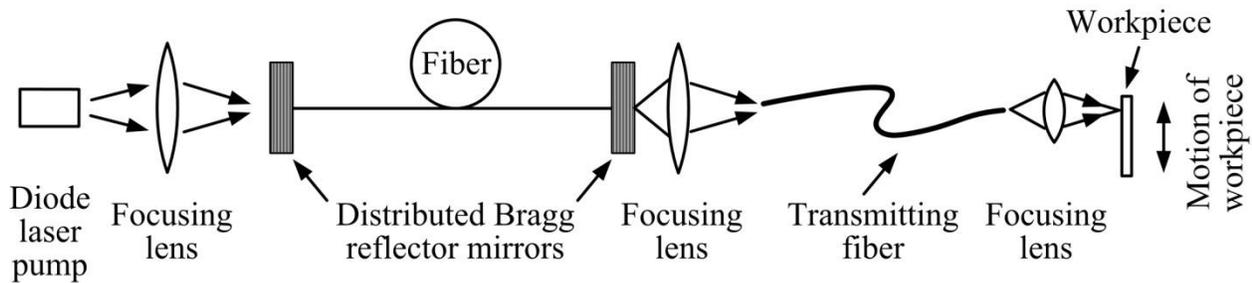


Figure 1 Typical arrangement for welding with a fiber laser.

Fiber lasers have been used in the conduction mode for welding razor blades, diaphragms for medical devices, cases for pacemakers and other thin samples. The power needed for such welding has usually been in the range of some hundreds of watts. One study demonstrated conduction welding of stainless steel by a continuous ytterbium-doped fiber laser emitting 360 W at a wavelength of 1070 nm. Welds from this laser could be made at a speed of 50.8 mm/sec and has reached a depth of 0.89 mm. Conduction welding of 0.5 mm thick stainless steel at 1 meter/minute has also been demonstrated with only 100 watts of fiber laser power.

Because fiber lasers now are available with multi-kilowatt output power, they have also been used to make deeper welds in the penetration mode. A study compared the depth of penetration welds in mild steel as a function of welding speed at the 3.5 kW level for fiber, CO₂, and Nd:YAG lasers. The study covered the range of weld speeds from 1 to 10 m/minute. At all weld speed values except the very lowest (< 1.5 m/minute), the fiber laser produced the greatest welding depth.

In a test of penetration welding of stainless steel with 6 kW of fiber laser power at a wavelength of 1070 nm, the welding conditions (focus and weld speed) were varied. A fairly broad region of weld parameters was found in which the welds were sound, with no porosity or other defects. The maximum depth in which this no-defect welding could be produced was around 7 mm. These results demonstrate the ability of fiber lasers to produce high-quality welds.

Fiber lasers have also made high quality welds in aluminum. Welding thick aluminum has been difficult with other lasers. The high reflectivity of aluminum near 10 micrometers makes the CO₂ laser a poor choice. In the automotive industry, Nd:YAG lasers have frequently been used but their lower CW power has limited the throughput. In contrast, butt and overlap welds have been made in aluminum 6 mm thick with a 7 kW ytterbium-doped fiber laser. With the beam focused to a 0.5 mm spot, welds could be made at a speed of 3 meters per minute. The welds had complete penetration and were of excellent quality with very few defects and a narrow fusion zone.

Materials that have been welded with ytterbium fiber lasers include stainless steel and other types of steel, titanium and aluminum alloys, and Inconel (a nickel alloy). Applications include butt welding titanium panels, conduction welding of diaphragms, full penetration welding of transmission gears and shaft assemblies, and welding of thick steels.

The reason that single-mode fiber lasers produce excellent results for welding (and for cutting as will be described later) when compared to other high power lasers is their excellent beam

quality. This allows the beam to be focused to a very small spot size producing high irradiance at the target surface.

Cutting

Lasers have long been used for cutting, for example the cutting of metals in the automotive industry. The laser of choice that has been used most often is the carbon dioxide laser, often at a multi-kilowatt level. Now fiber lasers with multi-kilowatt output are commercially available and are competing for metal cutting applications. As an example, a study using a fiber laser emitting 400 watts of power at a wavelength of 1075 nm reported cutting rates around 2 m/minute for 2 mm thick stainless steel and about 6 m/minute for 2 mm thick mild steel. These cutting rates increased substantially as the sheet thickness decreased. The cut edges were of high quality with little dross and small heat-affected zones.

Another study compared cutting rates at 4 kilowatts of power from a fiber laser and 4 kilowatts from a carbon dioxide laser. The fiber laser cut relatively thin samples (1 - 2 mm) at speeds about 5 times faster than the carbon dioxide laser. For greater thickness (10 mm) the fiber laser cut about 1.3 times faster. These results indicated that fiber lasers are valid candidates for sheet metal cutting applications.

The manufacturer of one type of fiber laser combined a fiber laser with linear-motor axis drives to create a complete laser cutting system for sheet metal. They demonstrated that their system cuts maintenance costs by up to 40% as compared to CO₂ laser cutting systems. They have shown that their system can cut mild steel two to three times faster.

Effective cutting with fiber lasers has also been demonstrated for non-metals, including plastics, acrylics, polycarbonate and leather. Practical examples of cutting with pulsed fiber lasers include cutting silicon wafers for solar panels and stencil cutting. High power multimode fiber lasers have been used for CW cutting of metals ranging from thin sheets to heavy plate for a variety of applications. The large depth of field and small spot size of fiber lasers lead to small kerfs and straight walls -- even in thick metals. Common applications with high power multimode fiber lasers include cutting automotive body parts like hydroform tubes.

Micromachining

Lasers have found many applications in micromachining. They have been used for applications such as producing medical devices like stents, drilling holes for microvias in circuit boards, patterning of thin films, and repair of semiconductor memories. The properties that are needed for these applications include high peak power for rapid material removal, short pulse length (nanosecond regime) for vaporization without producing a large heat-affected zone, good beam quality for focusing to a small spot, and high pulse repetition rate for high volume production. Reasonably high average power is also desirable. Frequency-doubled or tripled Nd:YAG lasers have dominated these applications for many years. But fiber lasers have all the properties listed above and are now competing for these applications.

Marking and Engraving

Lasers have long been used for marking products. They have been used to imprint product identification, barcodes, serial numbers, logos, etc. Materials used in the marking process have included metals, plastics, glass, stone, wood, cardboard, jewelry, etc. The laser used for a particular application is chosen with a wavelength that is absorbed by the material to be marked. CO₂ lasers have been used for materials like plastics and wood, which have high absorption near 10 micrometers, while Nd:YAG lasers have often been used for metals, which are reflective in the far infrared.

Laser marking may be performed in several different ways. It may be in a dot matrix format, in which the laser is repetitively pulsed and the beam is directed from pulse to pulse to different spots on the target so as to form an alphanumeric character. In another technique, the laser beam may be spread over a broad area so as to strike a reflecting mask in which the desired pattern is defined by vacant areas in the mask. Using this technique, the entire pattern is formed in one laser pulse. Engraving is another way to mark materials. Engraving involves the scanning of a laser beam back and forth over the area to be marked while modulating the power to change the depth of material removed. Engraving may be used to form complex patterns like company logos. Fiber lasers are well suited for any of these methods of marking. Because of their high beam quality, they may be focused to small spots useful in dot matrix marking. Pulsed fiber lasers with high pulse energy are suitable for mask marking, since they are easily modulated by direct modulation of the diode pump laser.

Marking by Q-switched fiber lasers with nanosecond pulse duration has been demonstrated for many materials, including glassy carbon, copper, silver, plastics and polymeric materials. The high values of peak power available are important for such marking.

As an example of using fiber laser marking, a fiber laser with a beam scanning system included is being sold for applications in bar code marking of metal tools and parts, and plastic components. The 24" x 12" area covered by the scanning system can contain one large part for processing or could hold many smaller parts to treat simultaneously. The cost of this commercial system is claimed to be about 30% less than that of a Nd:YAG laser system with comparable capabilities.

Wafer Processing

Fiber lasers can be used in the semiconductor processing industry, particularly for cutting and dicing silicon or other crystalline wafers on which integrated circuits have been fabricated. Cutting of silicon using a diamond saw has been common in the semiconductor industry. But diamond saws can cut only in straight lines and there can be problems with breakage. Other methods tend to be slow or expensive. The problems with cutting of silicon wafers continue to grow worse as the density of circuits on them increases.

The cutting of silicon wafers can be accomplished with 200 watts of CW power from a 1075 nm wavelength fiber laser. For 1.4 mm thick silicon, the cutting rate was measured at 0.7 m/minute. The cutting rate increased for thinner samples, reaching speeds greater than 6 m/minute for 0.5 mm thick samples. The cut edges were smooth with no cracking. Moreover,

the fiber laser could cut in patterns other than straight lines. Commercial models of such equipment are available.

Also, there have been limitations on cutting and separating very thin (less than 100 micrometers) silicon wafers. The yield can be unacceptably low using conventional techniques. Laser cutting has been used but the thermal effects cause a reduction in the fracture strength. An investigation of the cutting of 50 micrometer thick silicon wafers by 700 femtosecond duration pulses of near infrared radiation from a fiber laser-amplifier combination showed smooth walls with very little debris when the wafers were processed at a high scan speed and a high pulse repetition rate (500 kHz). Under the same processing conditions, the fracture strength of the cut wafers remained high. This was attributed to the very low heat effect that resulted from such short pulses. These findings could lead to use of fiber lasers for semiconductor processing in the future.

Other Applications

Although fiber lasers have widely been used for materials processing, there have been many other applications investigated. This section will examine some of these.

Telecommunications

Laser based fiber telecommunications systems using fiber optic links have been in widespread use since the 1970s. The laser source has most often been a semiconductor laser diode. Now the fiber laser offers an alternative choice that has advantages. For Instance,

- Erbium-doped fibers emit at a wavelength near 1550 nanometers, the wavelength which is most favorable for well-developed glass transmission fibers. Such fibers have the lowest loss near that wavelength. Thus the erbium-doped fiber lasers have a very desirable wavelength.
- The emission from a fiber laser comes out of a fiber, so it is relatively easy to couple the light into a fiber for long distance transmission. It is simple to join the laser fiber and the transmission fiber by fusion coupling. This is in contrast to the use of semiconductor diode lasers as sources, from which the light is emitted over a broader angle and which is more difficult to couple into a fiber.
- For communication applications, a passively Q-switched fiber laser offers high pulse repetition rates, up to at least 100 MHz. This is compatible with high data transmission rates.
- Fiber lasers are very reliable and maintenance free.

With all these advantages, fiber lasers are becoming popular in the telecommunications industry and their use will continue to grow. Figure 2 shows a possible fiber laser communications source. The fiber Bragg gratings are distributed Bragg reflectors formed within the end portions of the laser fiber. The laser fiber and the transmitting fiber are coupled end to end.

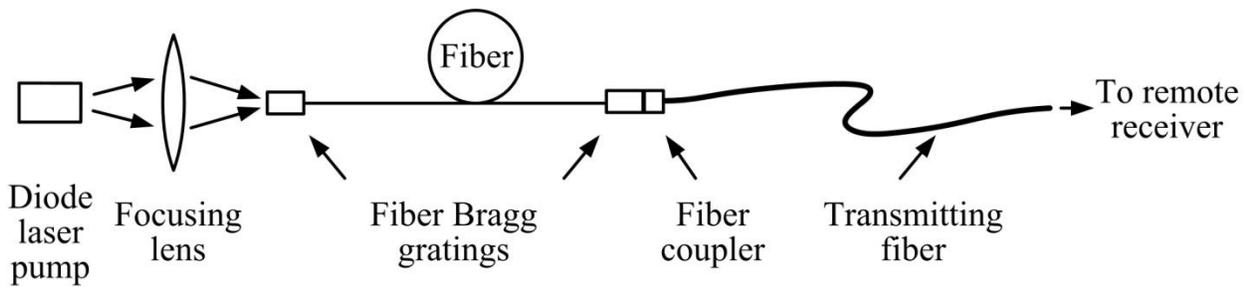


Figure 2 *Conceptual design for a fiber laser communications source.*

Spectroscopy

Fiber lasers have been used in a variety of scientific investigations involving spectroscopic studies of atoms and molecules and more macroscopic objects including solids, liquids and gases. Fiber lasers offer many advantages, including small size, portability, low maintenance and reliability. Tunable titanium-doped sapphire lasers have been widely used for laser spectroscopy, but because of the same advantages mentioned for telecommunications, fiber lasers are becoming popular alternatives.

This popularity in spectroscopy has spawned from the fiber lasers ability to generate very short pulse lengths in the femtosecond range that allows for high speed studies of the dynamics of atoms and molecules. Also, the high peak powers available in the green portion of the spectrum (when a near infrared fiber laser is frequency doubled) are in a region widely used for Raman spectroscopy which studies vibrational and rotational energy levels in materials. Of the many demonstrations of the use of fiber lasers in spectroscopy, we will present only two as examples. These are high resolution remote spectroscopy and two-photon fluorescence spectroscopy.

In the first example, an erbium-doped fiber laser was used in a scientific study to measure remotely the absorption of an oxygen molecular band in the 760 to 770 nanometer region. The motivation for this research was to determine atmospheric oxygen pressure at a distance. The application required an efficient, rugged laser operating in a single mode with high peak power. No other laser fulfilled the requirements well, so a fiber laser was developed specifically for this measurement. The erbium-doped fiber laser emitted radiation in the 1530-1540 nanometer region that was frequency doubled. The beam was directed at a solid target and after a 440 meter round trip, backscattered light that could be analyzed for oxygen was collected with a telescope. This demonstration showed successful remote oxygen sensing with a fiber laser and paved the way for longer path measurements.

The second example highlights a technique called two photon fluorescence spectroscopy. This technique used a commercial fiber laser emitting pulses with length less than 150 femtoseconds at a wavelength of 810 nanometers. Two photon fluorescence spectroscopy involves absorption of two photons from the laser and remission of the energy of the two photons as a single photon of shorter wavelength. The spectrum of the shorter wavelength light is analyzed to yield knowledge of the energy levels of the material being investigated. The fiber laser used in this

technique was smaller and less expensive than the possible alternative laser, the Ti:sapphire laser. The measurements included the temporal decay of the fluorescence produced by the simultaneous absorption of two laser photons in some fluorescent dyes and yielded results as expected from theory. This scientific work showed that fiber lasers were effective tools for performing precise spectroscopy measurements and were viable substitutes for other lasers typically used in these analyses.

Medicine

Fiber lasers have a variety of applications in the medical field, including marking and manufacturing of medical devices and direct irradiation of the body. The following examples give details of these applications.

Fractional Resurfacing

Fractional laser resurfacing is a technique for rejuvenating skin. It has been used for treating age spots, freckles, wrinkles and acne scars. Tiny spots are heat treated by the laser. In the treated areas the old skin is replaced by new, healthy tissue. This treatment has been successfully demonstrated and is gaining popularity. There is one fiber laser commercially available and designed for this treatment. It is an erbium-doped fiber laser emitting infrared radiation at 1550 nm. The laser radiation is delivered through a specially designed scanner to the skin which is to be resurfaced. The procedure must be controlled by a trained medical person skilled in the technique.

Marking Implants

Medical implants must be clearly marked for both tracking and identification. Methods like using ink or dye are unsuitable to mark these devices because they may cause contamination or allergic reaction. Lasers are used to create permanent, contaminant-free marks. There is no distortion to the surface. Fiber lasers with a beam that can be focused to a very small spot size accurately engrave characters as small as 0.3 mm. Fiber lasers can be used to inscribe areas which could not be marked by other methods.

Marking Medical Devices

Marking of devices and components is a common process in the medical industry. Fiber lasers have found use in marking medical devices such as forceps and clamps through a material ablation process. But a new method called dark marking, which does not remove material, has been developed using fiber lasers. This technique involves scanning the beam in a series of passes over the area to be marked. Typically the instruments to be marked are made of stainless steel which oxidizes on the surface when it is heated. After a number of passes, the color of the surface changes. This produces a dark mark which is easily visible. The marks are stable and are not removed in the processes used to sterilize medical devices. The fiber lasers that have been used in medical marking have been Q-switched ytterbium-doped devices emitting laser radiation at a wavelength near 1070 nm. Typically these lasers operate at 1 mJ with a pulse repetition rate of 20 kHz and pulse duration around 400 ns.

Manufacturing Medical Components and Devices

The manufacturing of medical components and devices involves materials processing procedures like welding and cutting. The use of fiber lasers for these operations has been described earlier, but now it will be discussed with special emphasis on medical devices.

Lasers have been used for welding surgical instruments made of expensive materials. These devices must be precisely fabricated to ensure surgeons have the control they need to perform various medical procedures. The fiber laser can achieve tolerances down to dimensions of a few micrometers. Another advantage of fiber lasers is their ability to weld strong, smooth, hermetic seals. This is important because many components are permanently implanted into the human body. They must not degrade or corrode over time. Since surgical instruments must be sterilized, their hermetic joints must be free from pores, so that they may be sterilized in an autoclave without causing damage to the instrument. Hermetic seals formed by fiber lasers are also important in fabricating pacemakers and sealing electronic components associated with medical devices used in the human body. Fiber laser welding also produces smooth, debris-free and clean welds without discoloration. This is the result of the highly controlled, localized heat input. The quality and good appearance of the weld are important factors for manufacturers of medical devices. Couple all of these advantages with the low operating costs and low maintenance of fiber lasers and the increasing use of them in medical component manufacturing become obvious.

Fiber laser cutting is important in the manufacture of surgical instruments and medical implants. Fiber lasers can cut many different materials with different thickness ranging from thin foil 50 micrometers thick to metal sheets several millimeters thick. The high quality of the fiber laser cuts result in kerf widths less than 20 micrometers in thin section metals. The heat affected zone near the cut is very small and the number of defects along the edge is very low. Cutting speeds of 10 m/min can be possible in metals, ceramics and semiconductors.

As an example, fiber lasers have been used for the fabrication of stents to be inserted into diseased coronary arteries to restore blood flow. The stents are similar to a woven metal mesh and have been fabricated by drilling many small holes into a thin metal tube made typically of stainless steel and nickel alloys. The material removal must be extremely precise. Stents are fabricated from tubes with diameters between one and ten millimeters and with wall thickness around 100 micrometers. It is clear that this process requires a very controllable laser. Fiber lasers with a high quality beam can provide this controllability as well as a very small spot size. In one demonstration of the use of fiber lasers for stent manufacture, the cuts were made with a 100 watt fiber laser. The cuts had high surface quality, no dross, a small heat affected zone and good appearance. In a comparison of the capability of fiber lasers and solid state lasers to produce stents, the rates of production of stents were similar for the fiber lasers and the solid state lasers but the fiber lasers provided cleaner edges with less slag. In addition, the fiber lasers occupied less space, required less maintenance and used less input power.

Microsurgical Applications

Fiber lasers are being considered for use in microsurgery. For such potential applications they offer advantages such as lower cost, low maintenance, high efficiency and compactness. As compared to other lasers they do not need an additional delivery fiber. In one experimental study researchers used a 110 watt thulium-doped fiber laser to vaporize prostate tissue. Another group of researchers is using ytterbium, erbium and thulium fiber lasers for studies of soft tissue surgery in the areas of urology, dermatology and ophthalmology. Still another group is studying the potential uses of an erbium-doped fluoride glass fiber laser for microsurgical applications in ophthalmology and otolaryngology. So far, these investigations are all in the realm of medical research. But there is enough interest in using fiber lasers for microsurgical applications that in the future we may expect them to emerge into clinical use.

Military Applications

The U. S. Department of Defense has exhibited substantial interest in fiber laser technology and is funding a number of research programs in this area. We note that these research programs are not for weapons but rather for applications like ranging, remote sensing and security.

Ranging

Laser-based range finding systems have long been available and have been widely used by the U.S. military. They operate by transmitting a short pulse of laser light and measuring the round trip time of the pulse from the laser to an object of interest. Since one knows the velocity of light, the distance of the object can be determined. The small, portable laser rangefinders now used in the field have limitations with a maximum range of around 10 to 20 kilometers and accuracy in the 1 to 10 meter region. This accuracy is set by the pulse duration, which in current systems is in the nanosecond regime. Fiber lasers, which are compact and portable, can emit femtosecond duration pulses with very high peak power. As a result, fiber lasers are now being seriously considered as replacements for the military's current ranging systems.

One demonstration has used an erbium-doped fiber laser operating at a wavelength of 1.55 micrometers. The detection system uses a beat frequency between the reflected light and a local reference signal. It is reported that this system has range capabilities up to hundreds of kilometers with an accuracy of one meter or less. Moreover, at this wavelength, the rangefinder is eye safe. In another demonstration a compact erbium-doped fiber laser has been developed for space and airborne light detection and ranging (LIDAR). This instrument uses kilohertz pulse repetition rates and 300 watts of power. It is intended for applications like mapping terrain elevation and for remote measurement of atmospheric composition. This too is an eye safe system.

Remote sensing

Thulium-doped fiber lasers have been developed for remote gas sensing. Thulium-doped fiber lasers operate at wavelengths in the 1800 to 2200 nanometer region. This wavelength region contains spectral absorption lines for many gases of interest, both for military applications and for industrial emission monitoring. In one application, the laser beam is transmitted to a fixed reflecting target and the strength of the reflected return signal is monitored. The laser is tuned

over a spectral range containing absorption lines of the gases of interest. A reduction in the return signal at a specific wavelength can identify the presence of a given gas and its concentration.

Security

Fiber lasers have been studied for their ability to detect and locate disturbances over long paths. This can provide enhanced security for military installations or for homeland security applications. In one use, a fiber laser co-doped with ytterbium and erbium and operating at a wavelength of 1550 nanometers was used. The laser, operating CW, was frequency modulated and part of the output sent via fiber to a nearby fixed reflector. The reflected return serves as a local oscillator. The rest of the laser light is sent through a long fiber which acts as the sensing element and is deployed over the area to be monitored. The light reflected from the sensing fiber and the light from the local oscillator are mixed and generate a beat frequency. The beat frequency is proportional to the difference in time delay between the two signals. If the sensing fiber is disturbed, the signal from the sensing fiber will change. The distance of the disturbance from the laser can be deduced from the altered beat frequency.

SUMMARY

This module has presented advantages fiber lasers have over other types of lasers, like efficiency, low cost, minimal maintenance and long lifetime. It has described the capabilities of fiber lasers for materials processing, like welding, cutting, marking, etc., and compared them to those of other more established lasers. Finally other emerging applications for fiber lasers, like communications, spectroscopy, medicine and military uses were discussed. Though fiber lasers are still relatively new, their obvious advantages will make them major enabling factors in future laser-based systems and create a large demand for technicians skilled at maintaining, calibrating and operating them.

EXERCISES

1. List at least six of the advantages of fiber lasers presented in the text.
2. Discuss briefly at least three of the materials processing applications described in the text.
3. Students should discuss the output power capabilities of fiber lasers.
4. State the efficiency of fiber lasers and compare it to Nd:YAG and carbon dioxide lasers.
5. A fiber laser operating in a single mode at a wavelength of 1100 nanometers has a core diameter of 55 micrometers. What is the beam divergence angle?
6. Name the applications (other than materials processing) mentioned in the text. Briefly describe at least two of them.
7. Why do fiber lasers have low maintenance requirements?

LABORATORY

Characterization of a Pulsed Fiber Laser at 1.06 μm

Materials

5W pulsed fiber laser system operating at 1064 nm.
Laser safety goggles (Minimum OD= 6-7 at 1064nm)
Power meter with the meter head calibrated for the laser wavelength of the fiber laser
Laser beam damp
Laser burn paper (to imprint burn pattern of laser beam)
Microscope slide cover slip (0.08 ~ 0.20 mm thick)
IR viewing card
Neutral density filter assembly
Fast photodiode (Rise time of 5ns or less)
Digital oscilloscope (Bandwidth of at least 200MHz)
Laser beam profiler

Procedures

The purpose of this laboratory is to characterize fiber laser output, including power, pulse duration, pulse repetition rate, beam divergence angle and beam quality factor. Students should not attempt this laboratory until they have studied the content of this module and completed the exercises. Students should read all laboratory procedures and the laser equipment manuals before beginning the laboratory. Proper safety precautions as outlined in the equipment manuals must be observed throughout the laboratory.

1. Read the user manual for the 5W pulse fiber laser.
2. Before turning the fiber laser on, carefully position the output fiber so it is horizontal and directed toward the center of the power meter head and other components. Be sure it is secured tightly in this position.
3. All people near the fiber laser while it is operating must wear safety goggles.
4. Measure a distance of .5 meters along the laser beam path starting at the output fiber end. Place a laser beam damp at this position so it will intercept the output laser beam. Remove any reflective components between the fiber end and beam damp.
5. Place the laser burn paper against the beam damp.
6. Operate the laser according to the instructions given by the user manual. Initially set the laser at its lowest repetition rate.
7. Once the burn pattern is imprinted on the burn paper, switch-off the fiber laser beam by closing the internal shutter.
8. Reposition the laser beam damp to about 1.0 meter from the output fiber. Place the laser burn paper against the beam damp and operate the laser to imprint another burn pattern on the paper. Once a burn pattern is established, switch-off the fiber laser beam by closing the internal shutter.
9. Measure the laser burn pattern diameters d_1 and d_2 obtained at the two different

locations of the beam damp, z_1 and z_2 . Calculate the half-angle of the beam divergence, $\theta_{1/2}$.

$$\theta_{1/2} \cong (d_2/2 - d_1/2)/(z_2 - z_1) \quad (\text{for small angles})$$

10. Place the power meter between the output fiber end and the last position of the beam damp, but closer to the output fiber. Zero the meter and tilt meter head slightly with respect to incident beam. This will prevent back reflections from returning to the fiber laser.
11. Switch on the fiber laser and operate the laser at its lowest repetition rate.
12. Allow the laser to operate for five minutes so that all temperatures in the system stabilize and then measure the average power. Set the laser at its other repetition rates (usually two other settings), measure the average power at each setting to complete the second column of Table 1. Note that the power meter is a thermal meter and thus, possesses a slow response to changes in radiation level. Allow five minutes between each power measurement for the meter to stabilize.
13. In order to measure the pulse duration, insert a microscope slide cover slip (0.08 ~ 0.20 mm thick, 92% of transmission) into the beam path at a 45° angle with respect to the beam path. Use an IR viewing card to locate the reflected beam and place the photodiode at this position.
14. Connect the photodiode output to the oscilloscope and observe the displayed pulse. Check and be sure displayed pulse is the actual laser pulse. If the photodiode is saturated, the display will show the peak simply "chopped off" or a distorted waveform. If saturation occurs, cover the photodiode with a few layers of lens tissue, or place a neutral density filter assembly in front of the photodiode, till the laser pulse is not clipped or distorted. Measure the repetition rate using the oscilloscope, and the full width at half maximum (τ). Complete the third column of Table 1.
15. Calculate the energy per pulse $E (= P_{avg}/f)$ and peak power $P_{peak} (= E/\tau)$ and complete Table 1.

Table 1 Fiber Laser Output Power at Different Operational Settings

| Rep Rate f (kHz) | P_{avg} (W) | τ (ns) | E (mJ) | P_{peak} (W) |
|--------------------|---------------|-------------|----------|----------------|
| | | | | |
| | | | | |
| | | | | |

16. Replace the photodiode with a laser beam profiler. Put the neutral density filter assembly in front of the beam profiler to reduce the laser power to an acceptable level (~ mW). Use the IR viewing card to align the laser beam properly with the beam profiler. Measure the beam quality factor M^2 , as well as the beam divergence angle. Record these values in the space provided:

Beam quality factor $M^2 =$ _____.

The half angle of beam divergence $\theta_{1/2} =$ _____.

17. Explain the meaning of M^2 measured in Step 16.
18. Is the measured beam divergence angle the same as your calculated value in Step 10? If different, what is the percentage error?

The percentage error = _____ %.

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