Recent Developments in Laser Sources for Industrial Applications

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Abstract- Remarkable developments and improvements in laser source technology for industrial manufacturing have taken place recently. Different technologies have continued to compete with each other on the benefit of the manufacturing industry. These include the full utilization of fibre laser toward becoming the dominant technology in laser manufacturing. This paper reviews the recent trends in the development and industrial use of high power fibre, diode, ultrafast, and other industrial laser sources. It is seen that these lasers are slowly replacing CO_2 and Nd-solid-state lasers that have dominated the laser manufacturing industry for decades.

Keywords: Diode laser, disk laser, fibre laser, ultrafast lasers, laser material processing

I. INTRODUCTION

LASER technology has recently gained popularity and established means of quickly and efficiently processing a variety of materials, whether by cutting, marking, engraving, drilling or structuring.

In a past paper [1], the authors presented work on the most important commercial types of lasers in terms of technological improvements in concept and design, their new applications and how they compete with each other on the market place. The leading industrial lasers that were described were: CO_2, Nd-doped solid state, fibre, ion gas, He-Ne, excimer and diode lasers. For each type, the type of active medium (atomic gas or solid-state,…), the wavelength emitted, main applications, recent trends, the main competing technology and a comparison of the market prices for the various systems were presented.en.

This is the case of fibre lasers. Its recent developments are such that this technology has stopped to be disruptive [2], to become the leader in almost all spheres of material processing [3]. Our interest in this paper will be about such fast growing technologies. We put our emphasis on fibre, disc, femtosecond and direct diode lasers. According to laser market analysts, the most active industrial laser technology product sector is the fibre laser both at low- and high-output power levels. Low-power pulsed and CW fibre lasers have revolutionalized the marking and engraving industries globally and are replacing Lamp-pumped solid state (LPSS) and Diode-pumped solid state (DPSS) lasers. High-power fibre lasers rapidly become a disruptive technology in the field of sheet metal, growing from miniscule annual sales in 2007 to today's market, where in 2012 more than 1000 of these kilowatt-level lasers have been integrated in flat sheet cutters capturing 20-25% of the market formerly held by high-power CO_2 lasers[4].

II. FIBRE LASERS

Fibre lasers were developed from the, Erbium-doped fibre amplifiers (EDFAs) used in long-haul fibre-optical communication systems**.** They are optically pumped, most commonly with laser diodes but in a few cases with other fiber lasers. The success of fibre laser is closed related to the development of strong, reliable and efficient pumping sources: diode lasers. The optics used in these systems are usually fiber components, with most or all of the components fiber-coupled to one another. In some cases, bulk optics are used, and sometimes an internal fiber-coupling system is combined with external bulk optics. A diode pump source can be a single diode, an array, or many separate pump diodes, each with a fibre going into a coupler. The doped fibre has a cavity mirror on each end; in practice, these are fibre Bragg gratings, which can be fabricated within the fibre. There is no bulk optics on the end, unless the output beam goes into something other than a fibre. The fibre can be coiled, so the laser cavity can be many meters long if desired. Some of the differences in technologies are brought into the sharpest focus by this example: a 50 kW CO_2 laser occupies the space of a small house, whereas the space occupied by a 50 kW fibre laser is closer to that of a large freezer cabinet. A fibre laser comprises a series of fibre components physically spliced together so the laser beam never leaves fibre-optic cable until it emerges from the fibre to be focused onto the workpiece. When this engineering approach is combined with the use of single-emitter pump diodes, the result is the most robust and longest-lasting laser tool available taking in account that the mean time between failures (MTBF) lifetimes for single-emitter pump diodes are 300,000 hand they are the ones to fail in the first place. The new developments in the fiber technology:

A. At the Low-Power End

At low power, sales of flashlamp-pumped laser markers have been eclipsed by low-power fibre laser sales and the development spreads in many directions:

(i) Nanosecond to microsecond pulsed fibre lasers

Nano- and microsecond fibre lasers of around 50W are used in ablation of coating and paints and in marking. The combination of high average power and high brightness is required to maintain the high ablation efficiencies. In fact, a derivative of this same laser type is available at up to 500 W

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average power with pulse energies up to 50 mJ. Exciting new applications for this laser include very high-speed removal of a range of films and coatings. The next generation of this laser type is already available with M^2 as low as 1.2, pulse lengths down to 1 ns, and peak powers up to 40 kW. Picosecond versions are in the pipeline.

(ii) Microsecond to millisecond high-pulse-energy fibre lasers

Another recent development is known as the quasi-continuous-wave (QCW) fibre laser. This is another extension of the fibre-laser concept that takes it into one of the last bastions of flashlamp-pumped laser technology: high-pulse-energy, low-duty-cycle laser processing. In this case, vertical integration and highly cost-effective manufacture of pump diodes, an understanding of nonlinear thresholds, and careful design have enabled a flexible range of lasers with maximum pulse energy of 60 J. The lowest-power-level laser at 150 W has a capability of 15 J and 10 Hz in a pulse length identical to that a flashlamp-pumped laser of 10 ms Trials have shown that the laser can not only produce the sort of large weld-nugget diameters required by many low-power welding applications but it is also capable of cutting high-reflectivity materials such as aluminum and copper up to several millimeters thick.

(iii) Temporally shaped millisecond pulses

The latest addition to the capability of the QCW lasers is a laser control package known as the pulsed signal generator (PSG). This allows a very high number of complex temporal pulses to be programmed. For sophisticated microwelding techniques such as dissimilar metal welding and welding of high-reflectivity metals, the pulse shaping capability is essential.

(iv) Longer-wavelength fibre lasers

Erbium and thulium rod lasers emitting in the spectral range of 1.5–2 μm have been in existence for some time but have not previously been used for materials processing. High-brightness fibre laser variants have been deployed in a variety of medical and airborne applications for a number of years. Many polymers have increased absorption at these wavelengths; it has only recently been established that this level of absorption is suitable for welding optically clear polymers, thus eliminating the need for specific IR absorbers. When using singlemode, high-brightness lasers, even collimated beams produce more than enough power density to produce high-quality optically clear joints in both the butt and lap weld configurations. Table 1 explains the superior photon efficiency of fibre lasers as compared to traditional neodymium lasers: fibre lasers are quasi-three-level systems and a pump photon excites a transition from a ground state to an upper level; the laser transition is a drop from the lowest part of the upper level down into some of the split ground states. This is very efficient: for example, ytterbium with a pump photon at 940 nm produces an emitted photon at 1030 nm-a quantum defect (lost energy) of only about 9% (see table).

TABLE 1
COMPARISON IN PHOTON CONVERSION FOR ND: YAG AND FIBRE LASERS [5]

Active element	Output	Pump bands	Photon conversion
Neodymium	1064-1088nm	808 nm	76%
Ytterbium	1030-1100nm	910,940,975nm	<90%
Erbium	1550nm	980 and 1480 nm	63% and 95%
Yb-Er	Erbium	Ytterbium	
Thulium	1750-2100nm	793 nm	41%

In contrast, neodymium pumped on its standard 808 nm pump line has a quantum defect of about 24%. So ytterbium has an inherently higher efficiency, although not all that efficiency can be realized because some photons are lost. Ytterbium can be pumped in a number of bands. Erbium can be pumped at either 1480 or 980 nm; the latter is not as efficient from a photon defect point of view, but is useful even so because better pump sources are available at 980 nm.

Overall fibre-laser efficiency is the result of a two-stage process. First is the efficiency of the pump diode. Semiconductor lasers are very efficient, with on the order of 50% electrical-to-optical efficiency. Laboratory results are even better, with 70% or even more of the electrical pump energy being converted into light. When this output is matched carefully to the fibre laser's absorption line, the result is the pump efficiency. The second is the optical-to-optical conversion efficiency. With a small photon defect, there high excitation and extraction efficiencies.

B. Configurations for Many Purposes

Fibre lasers are so versatile that they can be configured to operate in different regimes [6]:

(i) Q-switched fibre lasers

Q-switching operation is possible in fibre lasers, the principle being the same as for bulk *Q*-switched lasers. Typical pulse lengths range from low nanosecond up to the microsecond range; the longer the fiber, the more time is needed to *Q*-switch the output, producing a longer pulse. Fibre properties impose some limitations on *Q*-switching. Nonlinearities are more severe in a fibre laser due to the core's small cross-sectional area, so the peak power has to be somewhat limited. One can either use bulk *Q*-switches, giving higher performance, or a fibre *Q*-switch, which is spliced to the ends of the active part of the fiber laser.

(ii) Mode-locked fibre lasers

In modelocked fibre lasers, the repetition rate depends on the length of the gain material, as in any kind of modelocking scheme, while pulse duration depends on the gain bandwidth. The shortest achievable oscillator pulses are in the 50 fs range, with more typical durations in the 100 fs range. Shorter pulses can be generated in oscillator-amplifier systems with external chirped-pulse amplification and subsequent pulse compression.

C. High-Power Fibre Lasers

The industrial market is now the largest market for fibre lasers; much of the action right now is at the kilowatt-class power level. Particularly interesting is their use in automotive work. The automotive industry is moving to high-strength steel to produce cars that meet durability requirements but are relatively light for better fuel economy; the problem is how to cut the high-strength steel. And that is where they turn to fibre lasers. It is very difficult, for example, for conventional machine tools to punch holes in this kind of steel; however, fibre lasers (and other types of lasers as well) can easily cut these holes.

Fibre lasers have some advantages over other lasers for materials processing. For example, the near-IR wavelengths of fiber lasers are absorbed well by metals. The beam can also be delivered by fibre, which allows a robot to easily move the beam focus around for cutting and drilling.

Fiber lasers can satisfy extreme power requirements. The highest single-mode power available from a fiber laser is 10 kW, from IPG Photonics. In the system, a master oscillator produces a kilowatt of optical power that is fed into an amplifier stage pumped at 1018 nm with light from other fibre lasers. The entire laser system is about the size of two refrigerators. The highest multimode power reached is 50 kW, also by IPG Photonics [7]. The system relies on incoherent beam combination. Durability, very high power, flexibility, compactness and cost-effectiveness make fibre lasers attractive for industry. Other applications exist for fibre lasers in high-power cutting and welding—for example, replacing resistance welding for high-speed sheet steel, solving the problem of material distortion caused by resistance welding. Power and other feedback controls allow fibre lasers to cut a very precise curve, especially going around corners. There are also some laser applications we could not think of some years back:

(i) Drilling concrete

A 4 kW multimode fibre laser has been used to cut and drill concrete. Conventional percussion drilling can crack and weaken concrete, but fibre lasers cut it without fracturing. *Q*-switched fiber lasers are used, for example, in pulsed materials working, such as laser marking or working semiconductor electronics. They are also used for lidar; a module green module about the size of one's hand, contains an eye-safe erbium fibre laser with a 4 kW peak power, a 50 kHz repetition rate, and a 5-to-15-ns pulse duration [6,8].

(ii) Drilling for oil

This hybrid laser-mechanical process dramatically reduces energy requirements. Big drill rigs require about 2000 HP, equivalent to 1.5 MW. Powering a 20 kW fiber laser takes only 100 kW of power, and the drill needed to remove the softened rock requires only 10 HP, or 7.5 kW [9, 10].

Foro Energy (Littleton, CO and Houston, TX) has demonstrated that 20 kW of laser power delivered through a special optical fiber can drill through hard rock. The Foro process delivers the high-power laser beam to the rock surface, rapidly heating it to hundreds of degrees Celsius. The laser power is integrated with a mechanical drilling bit. The thermal shock "spalls" and softens the rock a couple of millimeters into the surface, then the mechanical drill clears it away.[

In terms of global laser revenues Table 2 shows the dynamics of the market on the high-power end of industrial lasers [11].

TABLE 2: COMPARISON OF GLOBAL ANNUAL SALES FOR MAJOR HIGH-POWER LASERS TECHNOLOGIES MILIONS OF DOLLARS

Type/Year	2011	2012	% change	2013	% change
CO_2	988	1016	3	1008	-0.8
Solid-state	424	453	7	450	-0.7
Fibre	495	576	16	616	7
Other	84	90	7	103	14
Total	1991	2135	7	2177	2

III. HIGH POWER DIODES LASERS

High-power laser diodes have seen tremendous development in the last two decades, first fueled by the demand for highly reliable pump lasers for use in EDFAs in telecommunication applications. For material processing, CO_2 gas lasers and diode pumped rod and disk lasers offer beam quality superior to that of direct diode lasers today. However, most applications do not require zero order mode beam profiles.

Today, the required output powers between tens of watts and several kilowatts are achieved from both fibre lasers as well as collimated laser diodes. This level has been enabled by the continuous improvement of power and brightness of the pump sources: diode lasers.

The competitiveness of systems directly using the collimated beams of diode lasers without the use of brightness converters like solid-state lasers is inevitably linked to the availability of high-power, high-brightness laser diode bars. A major breakthrough has been the introduction of stable AuSn solder technology, effectively eliminating degradation modes associated with intermittent operation [5]. Since the introduction of this solder, the available power levels have been continuously increased by improving the robustness and efficiency of the devices [12].

Today, bars with standard 10 mm emitting aperture on water-cooled micro-channel coolers (MCC) with a rated CW output power of 120 W[13] are used in commercial systems in high volume. Power degradation rates (wear-out) extrapolated from long-term testing of the bars have shown lifetimes in excess of 30,000 hours with only marginal increase of the drive current.

For commercial use in high power laser systems, the bars are arranged in vertical stacks, delivering for example 2.4 kW of output power from a 20-bar arrangement. Combination of several stacks by spatial beam shaping and polarization and wavelength multiplexing can deliver fiber-coupled output power of more than 850 W and 4 kW in a 400 µm and 1000 µm fiber core, respectively [14]. Free space delivery of up to 10 kW has been reported. Further power scaling of the laser bars has been demonstrated in the lab resulting in 425 W CW output power using standard MCC technology

The maximum conversion efficiency of transforming input electrical energy into light in diode laser bars is about 59%, which translates into a total electrical efficiency of about 40% for a high-power diode laser system. This is many times higher than for any other laser type. The primary benefit of this high efficiency is that it lowers the operating cost of the system since less electricity is required to produce a given amount of output power. Of course this reduced power consumption also decreases the carbon footprint of the laser's operation.

The small size of diode lasers makes them easier to integrate into workstations. It also means that they produce their waste heat in a relatively small physical area. As a result, they can be effectively cooled with a small volume of circulating water and a chiller [15].

A. Welding with high-power diode lasers

(i) Welding of metals

Direct diode lasers are best employed for conduction mode welding of thin metals for applications in which cost is a prominent factor (both purchase price and operating costs) and in which practical considerations such as floor space and part access are important. Additionally, the ability to deliver the output through long lengths of optical fiber provides a high level of flexibility in terms of where the laser system is located. It also enables beam delivery into tight or hard to access spaces. Typical uses would therefore be under-hood welding of components in automobile manufacturing and welding of heat-sensitive devices. Stainless steel is also well suited to conduction mode welding with diode lasers, particularly in applications where the corrosion resistance of the weld is critical. Typical examples are in medical devices, nuclear reactors and aerospace components. Again, this is because the lower process temperature doesn't cause removal of more volatile alloying elements from the fusion zone. Additionally, stainless steels are generally increasingly reflective at longer wavelengths so the shorter wavelength of the diode laser results in incrementally better light absorption and thus, higher efficiency than with older laser types. The higher absorption of shorter wavelength light is even more pronounced in aluminum which has a very significant dip in its reflectivity in the near infrared. Aluminum alloys containing volatile alloying materials such as magnesium, which is difficult to traditional keyhole laser weld can often be successfully welded with diode lasers

(ii) Polymer Welding

Laser beam welding of thermoplastics has advantages compared to other technologies like ultrasonic or vibration welding. Thermal and mechanical stresses for the welded parts are very low. It is non-contacting, clean and offers high-quality welding seams. High flexibility and easy joint design makes laser beam welding an accepted method for industrial production.

The method is well known. The welding partners are overlapping. One is transparent for the laser (LT), the other is absorbing (LA) and melts when exposed to laser radiation through the transparent part. Due to mechanical contact which allows heat transfer between the partners the laser transparent part is melting as well. The impact on the parts from a fixture or caused by the part design results in the mixture of the melt pools and after solidification the weld is formed [16]

(iii) Laser-assisted metal-plastic (LAMP), joining

Laser provides a solution to a difficult joining process - plastic to steel. Metals are strong and ductile, and plastics are light and easily formable. The importance of joining a metal and a plastic to take advantage of complementary qualities of the two types of industrial materials cannot be overemphasized. Traditional methods either using adhesives in the form of diverse glues or mechanical using bolts and screws all present some inconveniences [17] A laser joining technology for direct-bonding a metal and a plastic, named laser-assisted metal and plastic (LAMP) joining, has been developed to overcome the inconveniences. LAMP joining is performed by melting the plastic near the joint interface and then forming small bubbles in the melted plastic by utilizing a simple lap joint. The surfaces of plastic sheets and metal plates are cleaned with alcohol but other surface treatments are not required. If the plastic sheet has more than 60% transparency, it may be placed at the upper side. The transmitted laser beam is absorbed to heat the metal surface, and the plastic near the joint can be melted to form bubbles by the heat conducted from the metal. A shielding gas should be used to keep the top plastic sheet surface clean and cool. The procedure can be utilized on any plastic of high laser absorption. If the metal plate is thick, a partially penetrated weld should be produced to heat the plastic near the joint interface. The metal interface near the lap joint is not melted, but the plastic on the metal plate is melted to form small bubbles. The LAMP joining is applicable to bond thermo-plastics, especially engineering plastics, to any metal. High power diodes, like Nd: YAG and fibre lasers can be used in LAMP, with the advantage of the former of being cheaper more compact and presenting higher absorbing for metals than the latter [18].

B. Laser Soldering in electronic manufacturing

Laser soldering is a selective soldering technique which is used in electronics production for soldering contacts, sensors and switches. The advantages of this method are non-tactile heating, limited heat load, a highly defined, localized energy input and a good accessibility. Laser soldering is used when a thermal impact of surrounding components has to be avoided or when the components themselves are sensitive to heat. Contacting Flexible Printed Circuit boards (FPCBs) with conventional methods may cause laminating of the polymer compound and destroys the part [19]

The locally limited energy input allows the soldering of very small components. This can be demonstrated with a LED that has to be contacted to a thin copper wire. The diameter of the wire is 75µm. The pads on the semiconductor are gold plated and have a size of 400 µm x800µm. The solder has been applied to wires with a diameter of 300 µm. Visual and x-ray inspection show no porosity or imperfections.

C. *Laser Soldering in photovoltaic module manufacturing*

Lasers are already well established in solar cell production. Edge isolation with Q-switched Nd: YAG or Q-switched Nd: vanadate lasers are used to obtain high efficiency solar cells. Reverse contacting and separating the silicon wafers by drilling and cutting are typical laser applications in solar cell production.

All these technologies have in common that pulsed lasers with high peak power and very good beam quality, are used. High power diode lasers cannot compete with these features but have advantages when compact beam sources for CW applications with spot sizes up to millimeters are needed.

In photovoltaic module (PV) manufacturing the solar cells get interconnected by joining cell and ribbons using soldering methods. Most common are non-contact technologies like induction-, hot air-, lamp or micro flame soldering. To get a high yield it is essential to minimize the thermal and mechanical stress for the cell and therefore tactile methods like soldering iron become less important. It is also necessary for the solder joints to exceed certain dimensions to get both good electrical contact and mechanical strength.

The present trend in silicon solar cell production towards thinner (<200µm) and therefore cheaper layers demands for gentle production methods to reduce wafer breakage during module manufacturing. [20, 21]

Laser soldering with high power diode lasers has all properties for contacting thin film solar cells. The solder joints which can be achieved by using CW diode lasers have several square millimeters. Laser soldering is a non-contact technology with an accurate and locally limited thermal input. This limits the thermal stress for the cell. The high level of automation results in a very repetitive process. To increase the process stability, a closed loop temperature control of the solder joint by pyrometer is also possible.

Usually Si solar cells are interconnected by strings which then get laminated into the modules. This technology requires handling for the long and fragile strings with additional equipment. Using laser the string handling can be completely avoided by soldering directly on the laminate layers. This method is named In-Laminate Laser Soldering (ILLS) [22, 23].

Therefore we see that diode lasers are a flexible tool for welding and soldering processes in automotive, electronic and medical device manufacturing. Combined with adapted optics and a wide range of available wavelengths, cost effective and reliable solutions for automated production are possible. Especially with wavelengths around 2µm new applications which could not be addressed with lasers are possible now.

IV. DISK LASERS

The thin-disk laser (sometimes called active-mirror laser) is a special kind of diode-pumped high-power solid-state laser. The main difference from conventional rod lasers or slab lasers is the geometry of the gain medium: the laser crystal is a thin disk, where the thickness is considerably smaller than the laser beam diameter. The heat generated is extracted dominantly through one end face, i.e., in the longitudinal rather than in the transverse direction. The cooled end face has a dielectric coating which reflects both the laser radiation and the pump radiation [24]. The disk laser design benefits from five unique properties [25]:

(i) Virtually no thermal lensing due to axial heat flow enables high brightness of the disk laser.
(ii) Low brightness requirements of the pump diodes enable cost effective lasers with high electrical to optical conversion efficiency - especially in the high average power regime.
(iii) Area scaling of the beam cross section enables power scaling while keeping constant internal intensities.
(iv) Deep gain saturation eliminates harmful back reflection problems which are commonly encountered in fiber laser systems
(v) The modal cross sections are generally large compared with the longitudinal extension of the gain medium. Therefore high peak power sources are possible without facing problems due to nonlinearities.

The disk laser's output can be scaled in two ways. Firstly, the output power per disk scales directly with the power of the pump source. The pump source of a disk laser consists of discrete modules. The number of pump modules can be adjusted to fit the desired output power per disk, which enables easy field upgradability. Secondly, several disks can be arranged optically in series, further increasing the possible output power at constant beam quality. Serial combining within a single resonator is the preferable approach because simpler optical layouts can be used. Up to four disks have been connected in series.

Commercial systems with 4 disks achieve an output power of 16 kW, which is equivalent to 4 kW per disk.

Until now, experimental investigations have not reached any fundamental limitations of maximum output power per disk.

Calculations from the University of Stuttgart indicate that 30 kW from one disk are, in principle, possible [5]. The most brilliant disk laser so far has been built by Boeing [26]. A nearly diffraction limited beam quality" suitable for tactical laser weapons" has been achieved at a remarkable output power of more than 27 kW. With intracavity frequency conversion, 700W an output power of 700 W at 515 nm and a repetition rate of 100 kHz from a Q-switched Yb: YAG thin-disk laser [27].

V. ULTRAFAST LASERS

The development of a diverse range of laser sources operating in the femtosecond time domain, and more recently in the sub-femtosecond region, has been a consistent theme within the photonics research sector for much of the past two decades. As long as ultrafast lasers solid-state lasers are concerned, the Ti: sapphire laser remains a foundation on which many subsequent system developments have been based, a common and desirable feature is that the gain media should lend themselves to diode laser pumping and facilitate access to smooth and broad lasing spectra.

In particular, Cr^{3+}-doped colquiriites (Cr: LiSAF, Cr: LiCAF, and Cr: LiSGaF) (0.8-0.9 µm) represent currently low-cost alternatives to Ti: sapphire laser technology. Cr4+-doped Mg_2SiO_4 (forsterite) and $Y_3Al_5O_{12}$ (YAG) laser systems are able to support the generation of high-energy sub-50 fs pulses in the 1.3 µm and 1.55 µm regions which are ideal for many biological and datacomms applications.

Cr^{2+}-doped chalcogenide materials (Cr: ZnSe, Cr: ZnS) are an attractive option for broadband femtosecond laser developments in the mid-IR (~2.4 µm) which are especially well suited to sensitive and high-resolution molecular spectroscopy [28].

Although crystalline gain media with rare-earth ion doping (Nd^{3+}, Yb^{3+}, Er^{3+}, Tm^{3+}, Ho^{3+}) do not offer such broadband gain spectra as their transition-metal counterparts, the distinctively attractive features of this class of laser include low operational threshold, high efficiency and an ability to be configured into extremely compact configurations. Indeed, pulse repetition frequencies up to 160 GHz and 100 GHz for picosecond-pulse generation have been demonstrated for Nd: YVO_4 [29] and Er: glass [30] mode-locked oscillators operating around 1 µm and 1.5 µm, respectively.

Currently, ytterbium-based femtosecond lasers produce pulses as short as 35 fs (Yb: YCOB) [31] and operate with an optical-to-optical efficiency that can reach 50%. When deployed in a thin-disk laser configuration that offers efficient heat removal capabilities, Yb-based lasers can generate average powers up to 141 W at a pulse duration of 738 fs (Yb:Lu_2O_3) [32]. It should be noted that higher average powers are only available currently from more complex oscillator-amplifier systems such as a fibre laser with a chirped-pulse-amplifier (830 W, 640 fs) [33] or using a slab amplifier (400 W, 680 fs) [34].

For ultrafast fibre lasers, femtosecond fiber lasers are based on transitions from rare-earth ions operating in the near-infrared and are often based on Yb-, Er- or Tm-doped gain media. Their relatively high peak powers are well matched to nonlinear optical conversion and indeed a range of commercial products are now available which give comparable performance to Ti: sapphire oscillators. These fiber laser systems are based on polarization-maintaining fibers. Reliable mode-locking is achieved with a saturable absorber mirror (SAM) [35]. The output from fibre lasers is also well matched to the photonic crystal fibres that are often used to generate supercontinuum radiation from which a range of all-fiber-supercontinuum sources have been developed. This versatility of performance when combined with their inherent practicality makes modern femtosecond fibre lasers a very important enlargement of the ultrafast source portfolio that is available to scientists and technologists for applications that now span a broad range of disciplines [36]

A. *Industrial Applications of femtosecond lasers*

Pico- and femtosecond lasers are now at the cutting edge of material micro processing in fields ranging from optoelectronics devices to eye surgery. Advantage of the ultrafast lasers lies in highly nonlinear interaction of short and intense light pulses with matter when ablation occurs without significant thermal impact. Minimization of thermally affected zone in the laser ablation process dramatically increases the machining precision and produces less damage to the surrounding material as compared to long pulse laser processing [37]

Femtosecond pulses have been shown to produce damage-free micromachining in silicon and many other materials. It is generally observed that femtosecond lasers ablate Si in a more controlled manner and therefore offer a great advantage as a tool for the precise micromachining of miniature devices, compared to for example UV third and fourth- harmonic Nd:YAG DPSSLs.

(i) Synthetic Diamond

CVD diamond is becoming an important material in a growing number of optical and optoelectronic applications, mainly due to its unique set of physical, thermal and optical properties.[5]. Laser processing options for CVD diamond include cutting, drilling, smoothing and machining (e.g. microlenses). Femtosecond pulses were used to laser smooth and cut wafers of CVD diamond with no evidence of graphitization problem which had been witnessed when other types of lasers including nanosecond-pulse infra-red Nd: YAG lasers and UV excimer lasers, were used.

(ii) Metals, Glasses, Ceramics and Optical Materials

Many other materials are also of interest in different laser applications, particularly in the MEMS/MOEMS field. The unique attraction of using femtosecond pulses was either the excellent quality of the results (especially the lack of thermal effects) or the fact that other lasers could not machine the materials (e.g. silica, fluoro-polymers).

(iii) Steel

The importance of steel in industry has attracted a lot interest for laser micromachining applications. Despite all the effort, difficulties remain to laser micromachine steel at micron scale level to high quality standards. Femtosecond laser micromachining of steel has been recently demonstrated and provides exceptional quality.

Despite the high quality achieved with femtosecond micromachining the laser technology is not mature enough to allow integration in industrial environments yet and other solutions have been put forward such as the use of powerful diode-pumped solid state lasers that can remove material at higher rates.

(iv) Photomask repair

There are several industrial applications of femtosecond in material ablation including photomask repair [38]. The advantage of ultrafast lasers in material ablation is mainly due to the fact that for laser pulses >> 1 ps, the process of ablation is dominated by thermal processes i.e. the material absorbs light, heat up and evaporates. For laser pulses<< 1ps, the material will be converted to a plasma on a tile scale shorter than that required to emit phonons and generate heat. Femtosecond photomask repair provides significant improvement in quality and placement of repair, it allows both ablative and additive repair and gives a high throughput and spatial control

(v) Micromachining of diverse materials [39]

Micromachining of steel, ceramics, silicon carbide, gold, platinum, tungsten and especially medical devices manufacturing can benefit from the higher quality offered by femtosecond processing. Photovoltaics is another area to benefit of ultrafast lasers in wafer thin film removal. Ultrafast lasers can be used in cutting transparent materials such sapphire. The display industry also benefits from such lasers in LCD screen and OLED manufacture. These lasers can be used for surface structuring, internal marking and nanoparticle generation [40]

We have to notice here that ultrafast laser in micromachining are in tough competition with other laser technologies, especially solid-state harmonic UV DPSSLs and UV excimer lasers. The drawback for ultrafast lasers in industrial applications where equipment costs and speed of processing are important factors, the femtosecond laser systems can appear relatively immature and expensive options when compared to other solid-state lasers and a careful choice needs to be made as to which system offers the best combination of micromachining quality and economic viability.

CONCLUSION

This paper has presented the recent advances in laser developments and applications in material processing. It has been seen that the technology for application of lasers in material processing in manufacturing has advanced tremendously and is, reliable and cost-effective. However, it is still a very dynamic and all time improving technology where everyday research and development introduces new approaches, principles and applications. Different technologies compete with each other on the benefit of the manufacturing industry. Since the year 2008, there has been a steady rise in the use of fibre, disc and ultrafast lasers for materials processing. These lasers are likely to replace CO_2 and Nd-solid-state lasers that have dominated the laser manufacturing industry for decades.

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