Fabrication of Pump Combiners for High Power Fiber Lasers

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Although traditional “heavy” laser machining is still employing CO2 lasers and micro machining is still relying on solid-state lasers, fiber lasers are experiencing an increasing popularity and rapidly gaining market shares, according to a recent market survey [1]. Prediction on the continuing double-digit growth of fiber laser applications for the next years is made even more reliable because preliminary reports on the global laser sales in 2010 highlighted that the effects of the 2008/2009 economic downturn have been overcome. Therefore, fiber lasers will be the key components for next generation of laser processing machines thanks to their excellent characteristics, such as:

• High efficiency (e.g. up to 4-5 times higher than that of gas lasers), with consequent benefits in terms of power consumption, and their possible use in green manufacturing processes;

• Superior beam quality, due to easy mode control and to simple thermal management related to the fiber geometry;

• Simplified output delivery, given the intrinsic guiding of the fiber that allows transporting the beam where needed;

• Improved reliability;

• Easy maintenance.

Today high power lasers make use of ytterbium doped silicate fibers, although new glass hosts and new dopants are tested in the research labs.

Typical high power fiber lasers are arranged in a configuration known as MOPA (Master Oscillator, Power Amplifier) in which the output of a low-power, high beam quality laser oscillator (MO) is amplified through several amplifying stages to achieve the required delivery power level, which is, in the case of continuous emission, in the order of few hundreds of W (Fig. 1). Then, many of these modules can be coupled together to obtain even higher power levels (e.g. exceeding 1 kW).

The MO is often a fiber laser itself (although other choices, such as using single-mode fiber pigtailed semiconductor lasers, are possible), while the PA is made by cascading rare earth-doped fiber amplifiers built on special fibers, such as large mode area (LMA) double cladding and photonic crystal fibers.

A critical component for both the fiber based MO and the PAs is the pump combiner (PC) since it has to guarantee an efficient coupling of high pump powers emitted from low brightness semiconductor laser diodes with the active fibers, while avoiding optical damages and signal back-reflections. PCs can be fabricated with two different functionalities:

Standard PC (also known as PC without feedthrough): all the input ports are made with the same fiber type and are used to couple the pump power into the active fiber; in the case of double cladding active fibers – the most common – the pump power is coupled into the inner cladding.

• PC with feedthrough: the central fiber of the bundle is a passive fiber with the core matching that of the active fiber to form a continuous path for the signal. Ideally, the back-reflected signal is confined into the core of the feedthrough and does not leak into the pump inputs, thus providing an automatic protection of the pump diodes.

• PCs with feedthrough are mandatory to pump the stages forming the PA, but they are often used in the MO too to exploit the protection of the pump diodes from the signal power leaking through the cavity mirrors. Typical schemes of PC without or with feedthrough are reported in Fig. 2-left, and in Fig. 2-right, respectively.

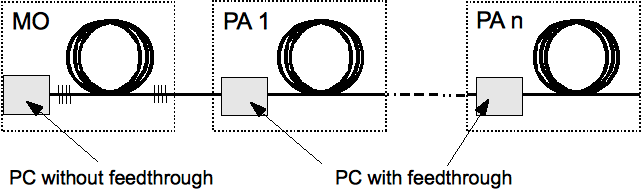


Figure 1. Schematic representation of the layout of a high power fiber laser. PC = Power Combiner, MO = Master Oscillator, PA = Power Amplifier.

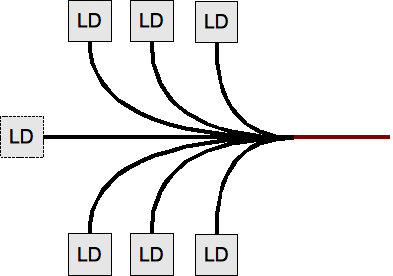
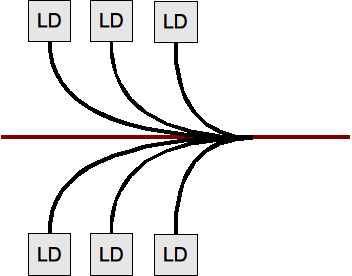
 

Figure 2. Schematic representation of a pump combiner without (left) and with the feedthrough (right). The red line

represents the single mode, double-cladding, passive fiber used either in the MO cavity or in the PA stage. Black lines indicate large core multimode fibers matching the outputs of the pump diodes.

PCs are based on a fused bi-conical taper (FBT) structure, which is fabricated by placing the required number of fibers adjacent to each other, and then fusing and stretching them to create a central coupling region. In practice, the procedure is more complex not only because the fibers have to be kept in the right position, but also because preliminary operations such as pre-tapering or partial etching in hydrofluoric acid might be required to fuse the bundle. PCs with feedthrough are particularly difficult to fabricate because the feedthrough fiber must be kept at the center of the bundle with tight tolerances throughout the fabrication steps. Moreover, geometrical constrains allow for fabrication of PCs based on the FBT structure with a defined number of input ports (7, 19, and 63 input ports are the most common), whereas brightness conservation poses constraints on the numerical aperture (NA) of the delivery fiber. PCs can be found as off-the-shelf components, although with a small number of input ports and for specific types of input/output fibers only. In many cases, however, and particularly for PCs with feedthrough, commercial products are often inadequate because, the PC must be properly tailored to the active fiber, matching its numerical aperture, mode distribution and geometry (e.g. single/double cladding, photonic crystal), to optimize the laser behavior. Hence, the necessity of a defined procedure for manufacturing, with good reproducibility, custom pump combiners with very high coupling efficiency. In a previous paper 2 , we presented the preliminary results on the development of such a procedure; here, we report on the improvements of the fabrication technique and on more in-depth characterizations of the manufactured devices.

*ниже дан перевод*

Хотя традиционная "тяжелая" лазерная обработка все еще использует CO2 лазеры, и микро механическая обработка все еще полагается на твердотельные лазеры, волоконные лазеры становятся все более популярными и согласно свежему исследованию конъюнктуры рынка быстро отвоёвывают свою долю рынка [1]. Все прогнозы сводятся к достоверной уверенности в продолжающемся двузначном росте приложений волоконных лазеров в течение следующего десятилетия, потому что предварительные доклады о глобальных продажах лазеров в 2010 году однозначно показывают, что эффекты экономического спада 2008-2009 годов были преодолены. Поэтому, волоконные лазеры будут ключевыми компонентами для следующего поколения машин лазерной обработки благодаря их превосходным характеристикам, таким как:

• Высокая производительность (до 4-5 раз выше чем, например, газовые лазеры), с вытекающим выигрышем с точки зрения потребления энергии, а также их возможным применением в производственных процессах с высокими требованиями к экологичности;

• Превосходное качество пучка из-за легкости контроля модового состава и распределения температуры;

• Упрощенное обеспечение вывода и подачи излучения из-за врожденных преимуществ волоконной передачи излучения и каналирования его в необходимую точку;

• Улучшенная надежность;

• Легкое обслуживание.

Сегодня волоконные лазеры большой мощности используют легированное иттербием кварцевое волокно, хотя в научно-исследовательских лабораториях ведутся интенсивные исследования новых несущих матриц и легирующих элементов.

Типичные волоконные лазеры большой мощности устроены в конфигурации, известной как MOPA (задающий генератор - усилитель мощности), в котором выходное излучение лазера малой мощности и высокого качества (МО) усиливается проходя через несколько каскадов усиления и достигает заданной величины мощности, которая в случае непрерывного испускания составляет порядка нескольких сотен ватт (Рис. 1). Далее эти модули могут быть соединены вместе, чтобы получить еще более высокую суммарную мощность в несколько киловатт.

Непостредственно МО как правило сам представляет собой волоконный лазер (хотя возможны и другие варианты, например, такой как одномодовый полупроводниковый лазер с волоконным выходом). При этом усилитель мощности (PA) представляет собой каскад волоконных усилителей, сделанных из оптического кварцевых волокон, легированных редкоземельными элементами, и специальной структуры, такой как большая площадь моды (LMA) с двойной оболочкой или фотон-кристаллические.

Критическим узлом как для МО, так и для PA является волоконный объединитель накачки (PC). Последний должен гарантировать эффективный ввод излучения накачки высокой мощности, испускаемого полупроводниковыми лазерными диодами высокой яркости в активное волокно, избегая оптических повреждений и обратного отражения излучения. PC могут быть изготовлены двух типов:

Стандартный PC (также известный как PC без сигнального канала): все входные порты сделаны из волокна одного тип и используются для ввода излучения накачки в активное волокно; в случае активного волокна с двойной оболочкой - наиболее распространенный случай - накачка вводится в первую оболочку.

• PC с сигнальным каналом (feedthrough): центральное волокно в жгуте - пассивное волокно с сердцевиной, равной по размеру сердцевине активного волокна, чтобы сформировать непрерывный путь для сигнала. В идеале, отраженный сигнал попадает обратно в сердцевину пассивного волокне, а не в волокна накачки, таким образом обеспечивая автоматическую защиту диодов накачки.

• PC с сигнальным каналом необходимы для накачки каскадов, формирующих PA, но они также часто используются в МО для предохранения диодов накачки от оптического сигнала, просачивающегося через зеркала резонатора. Типичные схемы PC без или с сигнальным каналом показаны на рис. 2.

Рисунок 1. Схематическое представление расположения элементов волоконного лазера большой мощности: PC - объединитель накачки, MC - задающий генератор, PA - усилитель мощности.

Рисунок 2. Схематическое представление объединителя накачки без (слева) и с сигнальным каналом (справоа. Красная линия представляет одномодовое, с двойной оболочкой, пассивное оптическое волокно, используемое как в резонаторе МО, так и в каскаде PA. Черный линии обозначают волокна с большим полем моды (с большой сердцевиной) согласованных с волокнами диодов накачки.

PC основаны на структуре сплавленного биконического тейпера (FBT), которая изготовливается путем размещения заданного числа смежных каналов рядом друг с другом (встык по боковой стороне), и затем их сплавления и растягивания, чтобы создать центральную область связи. На практике процедура более комплексна не только потому, что волокна должны быть удержаны в правильном положении, но также и потому что необходимы предварительные операции, такие как предварительное сужение или травление в плавиковой кислоте. PC с сигнальным каналом особенно трудно изготовить, потому что волокно сигнального канала должен быть сохранен в центре жгута с плотными допусками на каждом шаге изготовления. Кроме того, геометрические ограничения позволяют изготовливать PC, основанных на структуре FBT, только с определенным числом входных портов (наиболее распротсранены 7, 19, и 63), тогда как закон сохранение яркости налагает ограничения на числовую апертуру (NA) входного волокна. Большое число PC достпны коммерчески как стандартные волоконные элементы, хотя и с небольшим количеством входных каналов и для определенных типов волокон. Однако, во многих случаях, и в особенности для PC с сигнальным каналом, готовые продукты часто несоответствуют необходимым требованиям, потому что, PC должны быть должным образом состыкованы с активным волокном, согласованы по числовой апертуре, модовому распределению и геометрии (например, одиночное/двойное покрытие, фотонный кристалл), чтобы оптимизировать работу лазера. Следовательно, потребность в овладении процедурой производства с хорошей воспроизводимостью, волоконных объединителей накачки с максимальной эффективностью связи крайне высока. В представленной работе приведены результаты разработки такой процедуры; представлены усовершенствования существующих техник изготовления и всевозможные характеристики произведенных волоконных элементов.

Power Scaling Concepts in Fiber Lasers and Amplifiers

Jaclyn Su Phin Chan

A thesis submitted in partial fulfillment for the degree of Doctor of Philosophy

30 September 2011

Fiber-based laser and amplifiers have come a long way since the first fiber laser was demonstrated by Elias Snitzer in the early 1960’s [1]. In its early days, the growth of fiber technology was hindered by the lack of suitable pump sources. The advent of single mode pump diodes sparked a renaissance in fiber laser research, and in 1986, researchers managed to demonstrate the first practical erbium-doped fiber lasers [2].

These, however, were single mode devices which required pump sources to be similarly single mode, thereby raising the system’s cost and complexity. In 1988, the introduction of cladding pumping [3], whereby the pump light could be coupled into the much larger inner cladding of a double-clad fiber, removed this restriction, leading to a gradual rise in laser power. This increase has been spurred on by recently devised techniques like the fabrication of large-mode area fibers and the use of photonic crystal fibers. These developments in fiber technology have enabled the power scaling of continuous wave (cw) fiber lasers by almost 2 orders of magnitude over the past ten years, well into kilowatt levels (Figure 1.1), empowering fiber lasers with the potential to not only replace most of today’s conventional solid-state lasers as the laser source of choice, but also significantly broaden the field of laser applications.

Figure 1.1: Output powers for single Ytterbium and Thulium fiber oscillators over the years [4–14]

Fiber systems possess many attractive properties; they are superbly efficient, possessing a high electric to optical as well as optical to optical efficiency. Since both the waveguiding and gain is provided by the active doped core, the output beam quality of fiber lasers is usually very good. Single mode fibers in particular excel in this respect, not only in enforcing single transverse mode operation but also possessing some freedom from thermally induced mode distortions that regularly plague solid state systems.

The flexibility, strength, and durability of optical fibers mean that the component fibers in laser and amplifier systems can be coiled to relatively small diameters for compact packaging. In addition, improvements in fiber splicing techniques and fiberised optical components have enabled the production of monolithic, all-fiberised systems, with in-fiber pump and signal beam delivery, increasing its portability and robustness against external perturbations like vibrations, shock or large variations in temperature. Together, these two properties make fiber sources straightforward to manufacture and easy to maintain, and increases its appeal to customers who do not wish to be encumbered with overly fragile and bulky devices, allowing for competitive pricing in the marketplace.

Unlike conventional bulk solid state lasers that usually use crystalline hosts, fiber lasers and amplifiers use glass hosts, which means that they have broad emission linewidths and consequently a larger range of operating wavelengths. This, and the fact that fibers have very high gain, means that fiber sources can be operated over a wide spectral range with high efficiency. The myriad of possible combinations of fiber hosts and dopants, each with their characteristic emission wavelengths and wide bandwidths, further serve to extend the overall spectral coverage of fiber sources, particularly in the 1 µm to the 2µm wavelength regime (Figure 1.1).

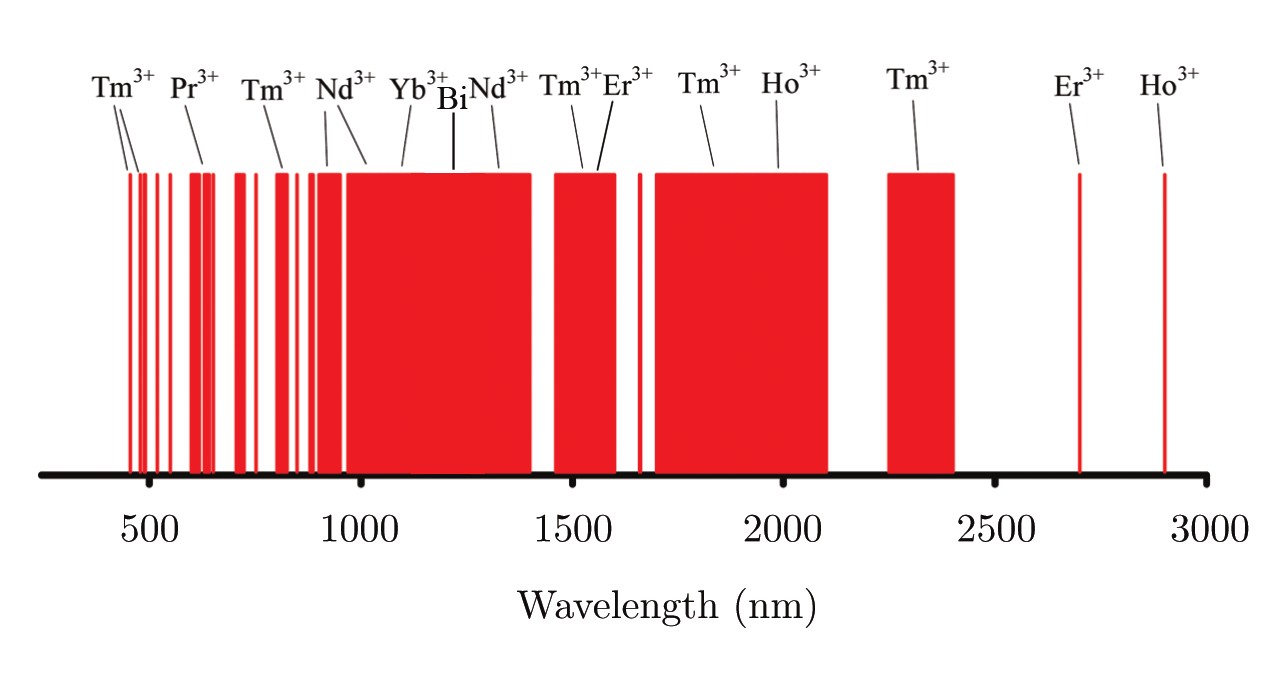


Figure 1.2: Operating wavelengths for fibers sources, displaying its wide wavelength coverage. Figure from [15]

Their large surface-to-active volume ratio gives fibers excellent heat dissipation and their long lengths mean that the thermal load due to heating effects is distributed over a considerably long distance. Additionally, exploitation of a fiber’s spectral characteristics e.g. via the usage of in-band pumping can reduce quantum defect heating and lower the thermal load further. This greatly reduces the demand on cooling mechanisms for applications.

Likewise the small core dimensions and long lengths enable very high gain values to be achieved in pumped active fibers, making them ideal for master-oscillator-power amplifier (MOPA) configurations. MOPA schemes, whereby the output of a low power seed laser is boosted by a high power fiber amplifier, is utilised by most commercial high-power fiber laser systems.

The uses of fiber devices are wide and varied. In general, its applications include welding, ablation, cutting, annealing, sintering, drilling, marking and patterning; fiber sources are versatile, effective, and increasingly important tools in industries ranging from manufacturing to medicine, food and packing to electronics and semiconductor processing.

There is a burgeoning commercial demand for high power and high brightness laser sources. As a matter of fact, the global laser market, currently valued at ∼ $1.5 billion, has experienced a healthy growth of 27% in the previous year - a positive trend that is forecasted to continue well into 2012 [16]. Further power scaling of the output power of fiber devices whilst maintaining excellent beam quality is thus crucial to keep up with the increasing demands of industry as well as to stimulate its expansion into new applications which would solidify its position among other types of lasers

*(здесь новая нумерация ссылок на литературу)*

2.3 Challenges of Power Scaling

In this section we examine the various factors that hinder power scaling, such as optical damage due to the high intensities involved, the onset of deleterious nonlinear processes like stimulated Raman scattering and stimulated Brillouin scattering, and the repercussions of overly high thermal loads such as coating damage and thermal guiding.

2.3.1 Nonlinear processes

As the intensity increases, the response of light propagating in dielectric materials becomes increasingly non-linear. This is particularly true of high-power optical fiber media, where the high optical confinement of the beam over a long interaction length is conducive for the generation of a whole host of nonlinear effects. While nonlinear optics is the subject of intense study in many fields and is useful for various applications, some nonlinear processes are a nuisance for the purpose of power scaling, as their possible detrimental effects include reduced output power and disruption of the spectrum and beam quality (and pulse shape, for pulsed lasers). The two more dominant nonlinear effects relevant to this work are Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS).

2.3.1.1 Stimulated Brillouin Scattering

Stimulated Brillouin Scattering is a nonlinear process originating from the interaction of the high-intensity electric field of the propagating light wave with acoustic phonons within the material (electrostriction), resulting in a periodic variation in the refractive index akin to a grating. These periodic variations act as a scattering mechanism, which retroreflects the incident light. As the optical intensity of the signal light increases beyond the threshold level of SBS, the amount of backscattered light increases as well, causing a rollover of the output power. Self-pulsing in CW lasers, which causes drastic temporal instability and increases the risk of damage due to random high-intensity pulses, have also been attributed to SBS [10].

The threshold power for the onset of SBS is approximated by [11]:

(2.2)

Here, A eff and l eff are the effective core area and effective fiber length respectively. l eff is defined for a fiber of length l with a loss coefficient for the ’pump’ signal α P as

(1 − exp(−α p l). g B is the Brillouin gain coefficient, which in silica is roughly g B ∼ 5 × 10 −11 m/W [12]. K is related to the polarisation state of the pump; K=1 for polarised light and 2 for unpolarised [13]. ∆ν P represents the linewidth of the laser signal which acts as the ’pump’ for SBS processes. ∆ν B on the other hand is the linewidth of the Brillouin gain, which in silica is typically on the order of ∼ 33MHz at 1 µm [14], and ~10MHz at 2µm.

In the limit of ∆ν P ? ∆ν B , i.e. for narrow-linewidth operation, equation 2.2 simplifies to the more familiar form

(2.3)

Consider the general example of a 5m long ytterbium doped fiber operating at 1064 nm, with a core diameter of 6 µm and a corresponding mode field diameter of 7.5 µm. Broadly speaking if the linewidth is 0.1 nm, the SBS threshold is ∼ 4.8 kW, but if the linewidth is halved to 0.05 nm, the SBS threshold decreases to ∼ 2.4 kW. The threat of SBS is thus more severe in sources that operate with narrow linewidths such as single frequency sources.

This expression is valid for CW and for pulsed operation if the pulse width t p is greater than the phonon lifetime T B , which is typically <10ns.

2.3.1.2 Stimulated Raman Scattering

The origins of SRS are analogous to SBS, but arises from interactions with optical instead of acoustic phonons. These optical phonons scatter the incident ’pump’ radiation (the laser signal) into a lower energy Stokes wave, with the energy difference lost as heat [15]. A portion of this wave is guided along the core in both the forward and backward direction, and in the case of long fibers, can accumulate substantial gain and amplification through stimulated emission.

The equations for the threshold is similar in form to that of SBS, that is [11]:

(2.4)

where the Raman gain coefficient g R has a maximum value of ∼ 1.5 × 10 −13 m/W in silica [16]. Strictly speaking, the above equation was derived for narrow-linewidth operation, but as the Raman linewidth is very broad the equations are still reasonable approximations for broad-linewidth lasers.

If the first Stokes wave reaches a sufficiently high intensity, it could in turn serve as a ’pump’ for further orders of Raman waves, further depleting the gain and clamping the main lasing signal further. We can imagine the impact of this in an amplifier scenario, where increasing SRS could couple power away from the signal into shifted wavelengths where laser amplification cannot occur. Furthermore, with the generation of each Stokes wave, more heat is dissipated within the core, increasing the thermal load on the fiber.

Considering again the hypothetical 5 m long ytterbium fiber mentioned above, we can see that the SRS threshold would be ∼2 kW . As such, if this fiber is operated in a relatively broadband regime ∆λ > 0.1nm, SRS processes would be a bigger concern than SBS.

The equations are valid for CW operation as well as for pulses of widths > 1 ns [17]. For pulses shorter than 1 ns, the effective length l eff becomes

W

where

=

Where ν pump and ν Raman are the velocities of the pump and Raman pulses in the fiber as determined by their respective dispersion relations.

2.3.2 Optical damage

Another constraint for power scaling is bulk or surface damage caused by electron avalanches driven by the laser beam electric field. These electrons transfer energy to the glass matrix, causing fracturing or melting, particularly towards the silica/air interface at the fiber end facets. Traditionally, the safe operating fluence limit in fused silica for a 1064 nm wavelength pulse was governed by:

J/cm 2

However, later publications e.g. [18] assert that for pulses 50ps or longer, bulk damage occurs at a fixed power level rather than a fixed fluence. This irradiance damage threshold is said to be

(2.6)

In theory, the thresholds for surface damage can be equal to the bulk thresholds, but in practice, due to differences in surface preparation techniques as well as surface quality, dust, surface defects, or scratches, surface damage thresholds can be a factor of 2 to 5 times lower than the bulk one. Surface damage issues can be alleviated by various methods such as expanding the output beam and consequently decrease the fluence at the air/silica interface (either by the use of fiber end caps or by using a larger diameter core), or by ensuring good quality end-facet preparation.

The fact is that the exact values for surface value have not yet been explicitly determined. However, the high power amplifier used by Gapontsev et al [19], which had a MFD of 14 µm, withstood output powers of up to 2 kW and consequently fluences of about 10 W/µm 2 , thus this value can be used as a reasonable operating limit provided all the other factors (end facet prepation, etc) have been taken into account [11].

2.3.3 Thermal effects

2.3.3.1 Coating damage

There are many physical mechanisms which contribute to heat generation within an optical fiber, such as quantum defect heating, absorption by impurities, excited state absorption and energy upconversion. Moreover, the increasing pump powers available from commercial diode sources mean increasing thermal loads imposed on a fiber. While, as mentioned in the Introduction, optical fibers generally possess excellent properties for thermal management, this is spoilt slightly by the low-index polymer commonly used as the protective outer jacket for the fiber. These fluorinated acryilate polymer coatings, chosen for their good optical properties and ease of application during the fiber drawing process, suffer from very poor thermal conductivities of k 2 = 0.24WK −1 m −1 [20] and begin to degrade at temperatures approaching T d ∼ 150 − 200 ◦ C [6].

We can estimate the heat deposition per unit length required to cause damage to the outer polymer coating from [21] P hmax = 4π(T d − T s )

(2.7)

where

T s = ambienttemperature

r clad , r poly = innercladdingandpolymercoatingradius

H 2 = heattransfercoefficientforpolymercoating

Applying this to a hypothetical situation with a fiber with a 400 µm cladding diameter and a 50 µm thick polymer layer, we can see that if a coating experiencing thermal load T d = 200 ◦ C is convection cooled (H 2 ∼ 10WK −1 m −2 ) at room temperature T s = 20 ◦ C, the maximum heat deposition per unit length the coating can withstand is ∼ 46.9W. From equation 2.7 we can see that increasing the fiber dimensions while reducing the thickness of the applied coating would have a positive effect on the longevity of the outer polymer coating. Increasing the fiber dimensions would also be helpful in terms of increasing the area over which the heat is distributed. However, in the long run the use of other coating materials or active cooling (which would increase the value of H 2 ) would be more sensible.

2.3.3.2 Thermal guiding

Another adverse effect arising from a large thermal load is the problem of thermal guiding, which takes place when the thermal gradient within the core changes the refractive index profile of the fiber material. Eventually, the thermal guiding competes with the original refractive index waveguiding, resulting in stronger mode confinement.

A stronger mode confinement, which results in a smaller mode area, would subsequently reduce the threshold values for nonlinear processes and damage as well as support the propagation of higher order modes which would degrade the beam quality.

The power limit for silica fibers imposed by this limitation is given by [11]:

l

where

η laser = optical – optical conversion

η heat = fraction of pump power turned to heat

k tc = thermal conductivity

dt = thermo – optic coefficient

This researcher conjectured that if the fiber mode area could be increased arbitratily, in a hypothetical situation with no limits on available pump brightness, the maximum obtainable output power for a laser would be 36.6 kW, limited by this thermal guidance phenomenon as well as the onset of SRS. However, we note that this requirement is for power scaling of single-mode fibers, with no clear mode selection technique in place. Hypothetically, then, this restriction can be lifted if a suitable method for enforcing single mode operation in a multimode fiber can be found.

*From Sun PhD*

1.2.1.3 Self-Focusing

Self-focusing is a nonlinear effect induced by the refractive index change when the optical medium is placed in an intense electromagnetic field[47]. The origin of the self-focusing stems from the optical Kerr effect in which the refractive index, n, depends on the light intensity I, n = n 0 +n 2 I, where n 0 and n 2 are the linear and non-linear components of the refractive index. n 2 is positive in most materials. The refractive index becomes larger in the regions where the light intensity is higher, usually in the center of the light beam. A transverse light intensity gradient will induce a transverse refractive index gradient that works as a focusing lens.

The light beam is focused by this lens and the peak intensity of the self-focused region increases which strengthens the focusing lens. The focused light beam will eventually induce beam filamentation or optical damage. The threshold of the self-focusing is given by[48]

(1.4)

where λ is the radiation wavelength in vacuum and α is a constant which depends on the initial spatial distribution of the beam. Assume a Gaussian beam in silica fiber, α = 1.8962, n 0 = 1.45, n 2 = 2.6 × 10 −20 m 2 /W, λ = 1.06 µm, then P cr = 4.5 MW. Self-focusing needs to be considered in pulsed fiber lasers and will be addressed in Chapter 7.

1.2.2.1 Thermal Fracture

Solid-state materials are stronger in compression than in tension, making the surface particularly susceptible to fracture due to the presence of tangential forces. Thermal-induced stresses can make the fiber surface vulnerable to cracks, scratches, and voids. The output power of laser leading to thermal fracture due to tensile-limited stress is derived in Ref. [49],

(1.5)

where η heat is the fraction of the absorbed pump power that is converted to heat, η laser is the optical-to-optical conversion efficiency, L is the length of the laser, R m = 2460 W/m is the rupture modulus of the silica glass[50], and a and b are the core and cladding radius, respectively. If we assume η laser = 0.6, η heat = 0.3, L = 1 m, a = 6 µm, b = 62.5 µm, then P fracture = 61 kW. This effect is not likely to be a limiting factor in the near future, although commercial fiber lasers have reached the 10 kW level.

1.2.2.2 Melting

When scaling up the power in conventional fiber lasers, the on-axis core temperature can exceed the melting temperature of fused silica. The output power leading to melting is given by[49]

(1.6)

where k = 1.38 W/(m · K) is the thermal conductivity of silica[51], T m = 1983 K is the melting temperature of silica[51], T c is the coolant temperature, and h is the convection heat-transfer coefficient (or film coefficient or film conductance). The convection heat-transfer coefficient can vary significantly depending on the cooling mechanism [52]. It may be as low as 1000 W/(m 2 · K) for forced airflow cooling or has high as 10,000 W/(m 2 · K) for forced liquid flow of the coolant. If we assume T c = 300 K, h = 1000 W/(m 2 · K) and other parameters as assumed in Sec. 1.2.2.1, then P melting = 1.2 kW. CW high-power fiber lasers can operate above this level, provided special attention is paid to system design and thermal management.

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Fiber Bragg gratings with enhanced thermal stability by residual stress relaxation

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Fiber Bragg grating (FBG) devices used for high power fiber laser systems and optical fiber sensors in harsh environments often need to be able to survive very high temperatures [1-3]. Although the FBG is usually referred to a ‘permanent’ refractive index modulation in the fiber core, exposure to a high-temperature environment may result in the bleaching of the refractive index modulation that forms the grating. The maximum temperature a conventional FBG (used for example in temperature sensors) can sustain is typically reported to be around 600 ºC, this arising due to the weakness of the germanium and oxygen bonds [4]. Many research projects have been undertaken to aim to increase the thermal stability of these grating structures, for example through experiments involving accelerated aging, pre-irradiation, the formation of type II gratings, specialist ion-doped fibers and the use of chemical composition fibers, etc. [5-9]. However, a level of reflectivity decay of the grating that is unacceptable for many sensor purposes is still seen to exist at elevated temperatures and thus high temperature sensors cannot be developed. Recently, regenerated gratings have been produced in B/Ge-doped fiber, which can sustain high temperatures, of over 1200 ºC [10, 11]. However, specially doped fiber is required for this type of grating inscription and hydrogen loading of the fiber is also required [10]. In the last few years, FBGs fabricated by use of femtosecond laser pulses have attracted considerable attention in research and the thermal stability tests show that femtosecond laser inscribed type II-IR FBGs exhibit excellent stability, at temperatures slightly in excess of 1000 ºC [12-13]. This is likely to be the result of a nonlinear self-focusing process where ultra high peak power locally affects the glass structure [2, 14]. However, good thermal stability cannot be maintained when the temperature is increased to 1100 °C or higher [12-13] and the gratings then rapidly decay. One of the limitations to achieving an improvement in thermal stability lies in the fact that the residual stress exists in all optical fibers during their formation process, which has negative effects on the fiber reliability and grating quality and consequent thermal stability. The residual stress results mainly from the superposition of the thermal stress, caused by the difference in thermal expansion coefficients between the fiber core and the cladding, and the mechanical stress induced by the difference in the viscoelastic properties of the two regions [15].

In this paper, results on the characteristics of femtosecond laser pulse-induced type II-IR FBGs written in non-hydrogenated SMF-28 fibers with relaxed residual stress through use of an annealing treatment at high temperature are presented. Such gratings exhibit excellent thermal stability at temperatures up to 1200 °C, showing a grating reflectivity and a resonant wavelength that are essentially unchanged for 20 hours, during the isothermal measurements. Moreover, the gratings written in this work have a clear potential to maintain a high thermal stability at temperatures above 1200 °C, which makes them attractive as sensing elements for monitoring applications where very high temperatures are experienced.

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