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WHITE PAPER

The rise of the Thulium Fibre Laser in urology

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In this article, I discuss recent advances in laser technologies that improve several aspects of laser treatments in urology. I focus on Bragg grating reflectors which are used as cavity mirrors in Thulium Fibre Lasers.

Introduction

Fibre lasers provide many advantages that are driving their adoption in a growing number of applications that until recently relied on other laser technologies (solid-state crystal lasers, gas lasers, semiconductors, etc.). Therapeutic applications of lasers have existed since their introduction in the 1960s, and have continued to multiply and be refined ever since. The therapeutic fibre laser represents a significant refinement as it opens up new possibilities to improve precision and control during surgical procedures. This is particularly the case in urology, where a newcomer, the Thulium Fibre Laser (TFL), has all the attributes to dethrone the Ho:YAG laser, which has been the gold standard for more than 20 years for lithotripsy and other laser treatments used in this branch of medicine.

Lithotripsy

Lithotripsy is a laser treatment whose purpose is to eliminate stones that can obstruct the urinary tract (the bladder, kidneys, ureters, and urethra). The laser is conveyed endoscopically through the patient’s natural pathways and then directed to irradiate the stones with the energy required to disintegrate them. We seek to obtain fragments of the smallest possible size, ideally to reduce the stone to dust. This helps eliminate the need to remove the fragments using a special basket or other surgical instruments, and to reduce the duration of the procedures and the risks of complications. The size of the fragments generally depends upon the irradiation conditions, which includes the wavelength and the duration of the pulses.

Ho:YAG lasers

The urological Ho:YAG laser is a solid-state laser using a flashlamp-pumped crystalline rod as the gain medium. The laser emits pulses at a wavelength of approximately 2100 nm. At this wavelength, most of the laser energy is absorbed by water in the first 400 µm near the tip of the optical fibre used to deliver the laser to the treatment site, making it safe to use in an endourological context. Ho:YAG technology has been gradually perfected over the years to improve treatments and counter certain problems such as retropulsion. This is somewhat similar to the recoil effect associated with a gunshot, as the disintegration of a stone produces a counter-reaction that ends up pushing the stones away and forcing the surgeon to look for them in the ureters, and sometimes in the kidneys. This lengthens the duration of the procedure, and in certain cases can prevent access to the stones. To counter this effect, manufacturers use a trick which consists of first creating a “vapor tunnel” with a short pulse of low energy, followed by the pulse itself which, by using this tunnel, will ablate the stones. Another improvement is that the maximum pulse repetition rate, initially limited to around 15 Hz, can now reach 100 Hz, a development spurred by the desire to quickly and efficiently reduce the stones to dust. This reduces the complicated and costly operating time spent handling the fragments.

Thulium Fibre Lasers

The TFL uses a thulium-doped silica optical fibre most often pumped using laser diodes emitting around 793 nm. In addition to its doped core, the active fibre has cladding that guides the pump photons that are gradually absorbed by the Tm ions from the entry point. Thanks to this double clad fibre, both the laser emission and the pump are guided, unlike the free space propagation used in the Ho:YAG laser. This architecture is naturally advantageous for endoscopic laser surgery, because the laser emission can be coupled almost directly from the laser’s output fibre to the endoscope’s fibre. In the case of the Ho:YAG laser, a system of calibrated lenses is required, and in practice it is impossible to couple light into a fibre having a core diameter of less than 200 µm. In comparison, with TFL, a fibre with a core diameter of 50 µm can be used.

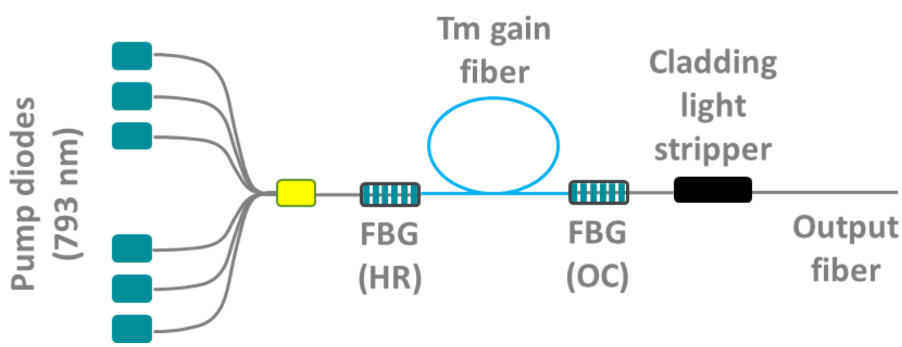

Figure 1. Main components of a TFL, including a pair of FBG reflectors that defines the laser cavity. HR: High Reflector. OC: Output Coupler.

The laser’s central wavelength, located in the emission spectrum of thulium, is determined by that of the Bragg gratings which serve as cavity mirrors (Figure 1). These gratings are fabricated in passive double-clad fibre compatible with active Tm-doped fibre. Urological TFL is usually designed to emit at 1940 nm. As this wavelength is closer to the water absorption peak than that of the Ho:YAG laser, the laser energy is absorbed over a shorter distance - four times shorter in fact. Given the exponential character of the absorption (the Beer-Lambert law), the TFL's radiation is absorbed approximately 16,000 times more than that from the Ho:YAG laser over a distance of 1 mm. This results in a much more confined laser-tissue or laser-stone interaction and a marked reduction in the minimum energy required to initiate vapor microbubble formation.

Advantages of Thulium Fibre Laser over Ho:YAG

Compared to Ho:YAG laser, the increased confinement provided by TFL translates into a four times lower ablation threshold. The consequence is that for a given energy, the TFL makes it possible to disintegrate a significantly larger volume of stones. As a corollary, the energy required to ablate a given volume is reduced. This makes the TFL less prone to the retropulsion effect. Increased containment also means safer treatment, with less risk of inflicting collateral damage to surrounding tissues.

In the case of the TFL, the pulses generated from the direct modulation of the pump diode current provide greater flexibility and better control of the irradiation conditions over generally wider ranges. While the pulses produced by the Ho:YAG laser have an irregular shape, typically comprising several peaks, those of the TFL present an almost rectangular profile with a peak power which varies very little over the duration of the pulse. This duration can be adjusted between 100 and 12,000 µs, compared to 50-1,300 µs for the Ho:YAG laser. The pulse repetition rate can be between 5 and 2200 Hz, while for Ho:YAG the maximum is only around 100 Hz (mainly limited by thermal lensing effects in the crystal). As for the energy of the pulses, the two technologies make it possible to reach a maximum of approximately 6 J, on the other hand the TFL provides a finer control in the bottom of the adjustment range, with a lower minimum energy (25 mJ vs 200 mJ for Ho:YAG). This is a valuable asset to generate the smallest possible fragments (dust) while keeping retropulsion to a minimum.

Several studies have demonstrated TFL's superiority in terms of effectiveness in urological treatments. Several factors explain this superiority. The very localized absorption of the radiation causes an explosive vaporization of the water trapped in the interstices, micro-fissures and pores located on the surface of the stone, which generates pressure peaks accompanied by waves of mechanical stress propagating in the whole of the stone. These stresses weaken the stone while removing debris from the irradiation site. In the case of the Ho:YAG laser, it has not been demonstrated that this mechanism intervenes directly in the ablation. The average fragment size is also reduced – in addition to producing more particles smaller than 0.5 mm than Ho:YAG, TFL can produce extremely small particles of less than 0.1 mm. This is real dust. The high repetition rates produce this dust at a higher rate than with the Ho:YAG laser. The major reduction in retropulsion is another determining factor in the duration of TFL treatments, as the surgeon does not need to constantly readjust the position of the fibre towards the stone.

Another advantage, the use of smaller diameter fibres results in greater flexibility with the endoscopes and the ability to treat otherwise inaccessible sites. The space freed up also enables increased irrigation and better visibility.

The TFL has many other advantages over the Ho:YAG laser, including nearly 10 times lower power consumption, no high-voltage circuitry, a seven times smaller footprint and eight times lighter weight. In an operating room, these reduced constraints greatly favor using the TFL. Add to that significantly lower maintenance costs, and this new technology becomes almost irresistible.

The TFL's cavity mirrors

The TFL's success in urology depends upon the availability of reliable components in the context of use specific to this type of laser, which includes cavity mirrors. These Bragg grating reflectors must meet the following basic requirements:

- 1940 nm central wavelength.
- Peak power handling of at least 600 W at 1940 nm (laser signal), for millisecond pulses
- Peak power handling of at least 1300 W at 793 nm (laser pump), for millisecond pulses.
- Availability for 25/400 format double-clad passive fibres (25 µm diameter signal core, 400 µm diameter pump cladding).

High-power fibre lasers are widely-used in the ytterbium band (typical wavelength 1080 nm) for industrial cutting and welding applications, with operating powers of 3 kW or more per cavity. Cavity mirrors that can operate at this power level are available from several vendors and are reliable because the technology is proven at this wavelength. Furthermore, there are specific challenges for cavity mirrors to operate in the thulium band. The main challenge is to keep the gratings from heating up, and the manufacturing processes used for the 1 µm gratings do not make it possible to provide the reliability expected at 2 µm. Instead, excessive grating temperature typically leads to fibre fuse type damage (Figure 2).

Figure 2. Excessive heating can cause fiber fuse type damage in FBGs.

TeraXion has launched the HPR Med-2 series cavity mirrors, which are Bragg grating reflectors specifically designed to meet the requirements of medical TFLs. Unique processes make it possible to considerably limit (factor 10) the heating of the gratings compared to conventional processes, as illustrated in Figure 3. This reduction in heating also results in a measurable reduction (up to a factor of 3) in the laser's wavelength shift as a function of output power, as shown in Figure 4.

With low insertion losses, Med-2 series reflectors help produce laser cavities that are less likely to initiate the phenomenon of self-pulsing, where high-energy pulses can cause significant damage to the components of the optical chain. The product can be configured for different cavity designs, whether in reflectivity, bandwidth or fibre type. The performance of these cavity mirrors is highly reproducible from unit to unit, helping to achieve equally-repeatable laser performance.

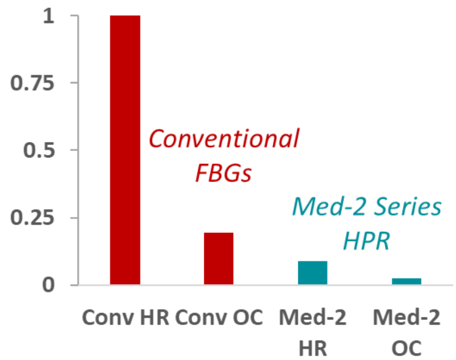

Figure 3. Relative heating of conventional vs TeraXion Med-2 series HPR reflectors.

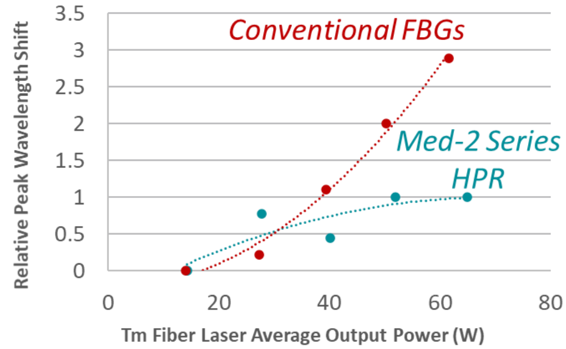

Figure 4. Relative laser peak wavelength shift vs output power with conventional vs TeraXion Med-2 series HPR reflectors.

Conclusion

With all their advantages, TFLs are expected to gradually replace Ho:YAG lasers used in urology. The transition has already begun, and TeraXion is proud to be part of it by offering innovative, efficient and reliable products specifically designed for this type of laser.

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