Mid-IR Fiber Laser for Medical Application

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***Abstract* — Tm doped fiber laser designed in a MOPA configuration has been demonstrated. At the incident pump power of 72 W, a maximum output power of 25 W was achieved, resulting in optical conversion efficiency about 35%. The output characteristics of the laser for different thermal regimes have been investigated.**

***Index Terms* — fiber laser, laser lithotripsy, splice losses, tissue ablation.**

The wavelength range around 2 µm covered by the mid-IR laser systems is part of the so called “eye safe” wavelength region which begins at about 1.4 µm. Until recently, advances in fiber laser technology have primarily focused on Yb-doped fibers operating around 1 µm. Much of the motivation for development of high-power 2 µm fiber laser systems has been for applications which would benefit from operating at eye-safer wavelengths, where permissible free space transmission levels can be several orders of magnitude greater than at 1 µm. Laser systems that operate in this region offer exceptional advantages for free space applications compared to conventional systems that operate at shorter wavelengths. This gives them a great potential for the use in LIDAR and gas sensing systems and for direct optical communication applications.

The favorable absorption in water makes such lasers extremely useful for medical applications. As it can be seen in Fig. 1, there is a strong absorption peak near 2 µm which reduces the penetration depth of this wavelength in biological tissue to a few hundred microns.

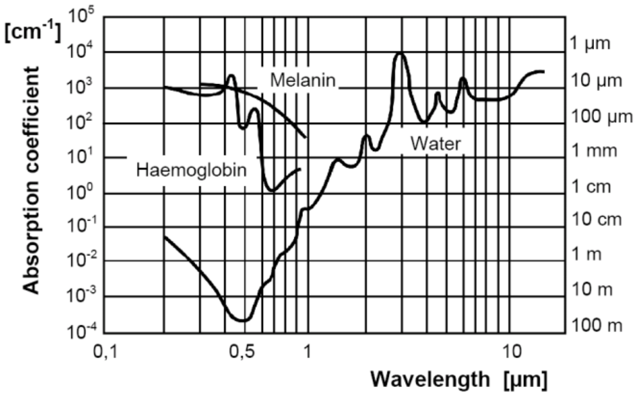

Fig. 1. Absorption and penetration depth in water and other biological tissue constituents for different wavelengths [1].

Due to the strong absorption in water, the main constituent of biological tissue, substantial heating of small areas is achievable. This allows application of the 2 µm lasers for highly efficient and precise ablation of soft and hard biological tissue. Additionally, bleeding during laser cutting is suppressed by coagulation and this makes 2 µm lasers ideal for many surgical procedures.

In modern medical practice laser technologies have a wide range of potential urological applications, including laser enucleation of the prostate and intracorporeal lithotripsy of urinary calculi. Laser lithotripsy is the most advanced and sparing method for treatment of urinary stones and can be performed under direct visual control through a flexible urethroscope [2, 3]. Effectiveness of fragmentation depends on stone size, mechanical properties, localization, as well as parameters of laser pulses and features of interaction of laser radiation with matter. Mechanical and strength properties are largely determined by composition and structural characteristics of stones. The change of micro-mechanical parameters of stones strongly depends on the following factors: wavelength of laser radiation, pulse energy and pulse duration, repetition rate, number of pulses in a train, features of radiation focusing conditions on the sample [3].

In laser lithotripsy, in dependence on laser pulse duration, fragmentation of concrements is due to two mechanisms. For Q-switched lasers (pulse durations < 500 nsec) stones fragment in result of photomechanical effects due to creation of shock waves inside the stone with instantaneous water vaporization and expansion of plasma bubbles produced while the interaction of laser radiation with the stone’s surface. For the long pulse lasers (> 1µsec) stones fragment in result of photothermal effects and ablation of material takes place directly due to the interaction of laser radiation with water-containing matter of surface layer of stone. Experience showed that the difference between laser lithotripsy devices that use photomechanical and photothermal mechanisms is derived primarily from the pulse duration and repetition rate, and not from differences in the wavelength [4].

For the long pulse 2 µm lasers, the mechanism of stone fragmentation is mainly photothermal, implicating a process of thermal drilling and less a shockwave impact (obtained using ultrasonic lithotripters), thus the risk of retrograde stone propulsion can be minimized.

Nowadays, the dominant tool commonly used for intracorporeal laser lithotripsy, i.e. urological stone fragmentation, is flash-lamp pumped Ho:YAG laser (λ= 2.12 μm) [5]. We propose diode pumped Tm fiber laser as a viable alternative for the Ho:YAG laser.

The Tm-doped fiber laser was designed in a MOPA (Master Oscillator-Power Amplifier) configuration, being composed, as can be seen in Fig.2 from two basic modules: master oscillator and amplification stage. For delivery of the laser radiation after amplification the output optical system is used.

The innovative diode pumped all-solid state design ensures highly reliable operation and thus no maintenance. Furthermore, considerably less waste heat is produced and therefore the thermoelectric cooling system generates negligible vibration and noise, compared to the well established water cooled flash-lamp pumped laser systems. The optional fiber-guided beam provides a convenient source for every day work.

The master oscillator produces a highly coherent beam, and the amplifier has the role to increase the oscillator laser output, but also to maintain the beam's properties. The global efficiency is mostly determined by the optical amplifier.

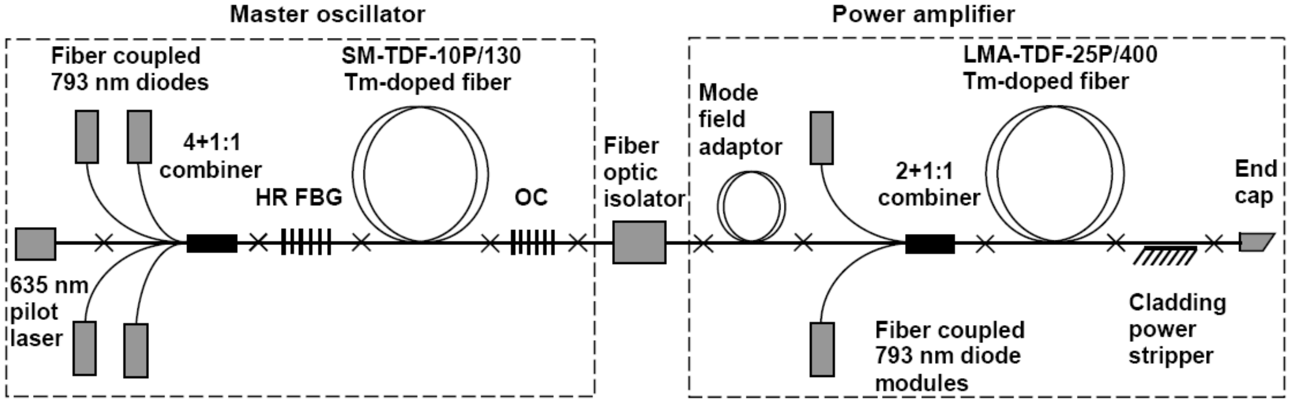

Fig. 2. MOPA Tm-doped fiber laser configuration

Fiber lasers are characterized by a very low oscillation threshold, therefore by a pumping threshold much lower than the nominal pumping level, absorbed in the active fiber. The active Tm doped fiber is sensitized with co-doping elements to ensure higher overall optical-to-optical efficiency and is optimized for the most efficient optical transfer of the 793 nm pumping radiation with a conversion ratio ≥ 50%. The pumping diode wavelength is 793 nm, thus the emission spectra of the diodes coincides with maximum of absorption spectra of the Tm doped fiber.

The master oscillator contains the following main elements:

- Tm-doped double clad fiber SM-TDF-10P/130-HE from NUFERN with diameters and numerical apertures equal to 10.0 ± 1.0 μm / 130.0 ± 1.0 μm and 0.15 / 0.46 for the core and first cladding, respectively.
- high-brightness fiber-coupled 793 nm, 4 W pump diodes from INTENSE.
- fiber optic power combiner (LightComm Technology Ltd), high reflective back (R ≥ 99.8%) and output (R=30%) fiber Bragg gratings from TeraXion.
- fiber coupled visible pilot laser (635 nm, 5 mW), spliced with signal input fiber of the combiner.

Small core active fiber facilitates highly efficient single-mode operation. Due to high peak core absorption (3.0 dB/m at 793 nm), the output power from master oscillator was about 3W at 12W pumping power.

The amplifier comprises Tm-doped double clad fiber LMA-TDF-25P/400 with large effective mode area also from NUFERN, fiber coupled pumping diode modules (LIMO, 793 nm, 35 W), power combiner, mode field adaptor that expands the mode field of the master single mode fiber to match the size of the fundamental mode of the multimode fiber in amplifier, cladding power stripper for removing residual pump light and angled end cap to reduce back reflected signal. Between the two stages the fiber optical isolator is used, a necessary passive component for prevention of unwanted light feedback into the high sensitive components of the master oscillator.

The active fibers feature low numerical aperture and high concentration Tm-doped core design. They are fully optimized for high slope efficiency (composition has demonstrated > 130% quantum efficiency) when pumped at 793 nm. This extraordinary efficiency is due to composition enabled cross relaxation of Thulium ions in the fiber core. The high Tm concentration allows short device lengths and high pump conversion efficiency while the low NA core design is ideal for applications where single-mode beam quality is critical. The high NA ≥ 0.46 pump cladding waveguide allows for efficient coupling of high pump powers. The large core diameter maintains a large effective mode areas and short cavity length, thereby minimizing non-linear effects such as stimulated light scattering, one of the major limiting factors on the amount of power that can be transmitted via optical fiber.

The fiber optic components were connected in all-solid state design with fiber fusion splicer FSM-100M from Fujikura which provides as low as 0.05 dB splice losses for dissimilar multimode fibers. The end faces of the fibers were preliminarily prepared with 3SAE liquid clamp cleaver with completely torque-free clamping system, which uses a metal alloy ingot. The cleaver produces very flat cleaves with angle offset 0-0.5 deg. for improved splice loss and beam quality. The second cladding coating around fusion spliced sections of the fibers was restored with protective UV cured low refractive index polymer.

Fiber lasers have a net advantage than all the regular solid state lasers from thermal management point of view, and so they represent a much better option in medium or high power operations. The fiber itself must be cooled to maintain the laser in efficient operating state and to avoid thermal damage of the low index coating polymer [6]. This is obtained by wrapping the fiber around cooled aluminum spool with a U-shaped groove cut around it. The groove keeps the fiber in place and helps cooling it better. For additional heat transfer the wrapped fiber is coated with highly thermally conductive (2.3 W/mK) silicon adhesive sealant.

Tm fiber laser has several advantages than the Ho:YAG lasers, mostly used until now in laser lithotripsy. It is more efficient, provides much higher repetition rate and average power and much better quality of the output laser beam. The Tm laser is light, compact and easily movable from one operating room to another.

The used laser diode drivers ensure CW operation of pumping diodes and 100% output power modulation with repetition rate of up to 0.5 kHz, therefore the laser can be used both in CW and modulated mode of operation with rise and fall times of <1 msec for ensuring a variable thermal coagulation or evaporation conditions of tissue based on the specific medical procedure. Due to the extraordinary high quality of the beam and better focusing, the 2 μm wavelength Tm fiber laser produces four times less thermal damage to the tissue than the 2.1 μm Ho:YAG laser, an important fact in high precision medical applications. The quality and small diameter of the beam permits better coupling in a surgical fiber with low core dimension for using it in extreme bending conditions in flexible endoscopes. The laser energy is transmitted trough ultra low OH$^-$ quartz optical fiber guided by an endoscope to be in direct contact with the tissue or urological stone’s surface. The most powerful effect takes place exactly at the end of the fiber. While emitting the laser radiation through the liquid environment, a microscopic bubble of water vapor with low absorption creates at the tip of the fiber, which allows delivering of all of the laser beam energy to the object, avoiding dispersion in the liquid medium around [4].

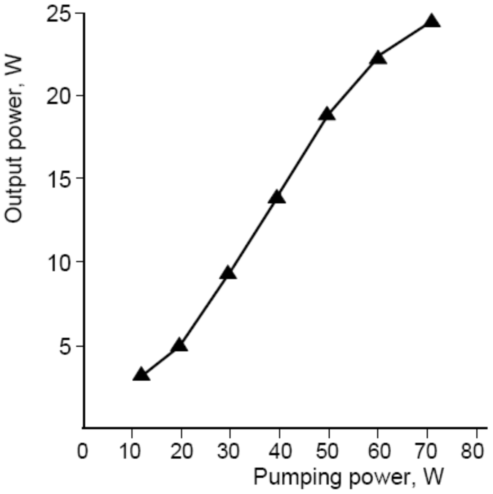

Fig.3. Output power versus input pumping power.

At maximum available total pumping power of 72 W and diode module base plate temperature 18 °C a maximum output power of 24 W was achieved, resulting in optical conversion efficiency about 33%.

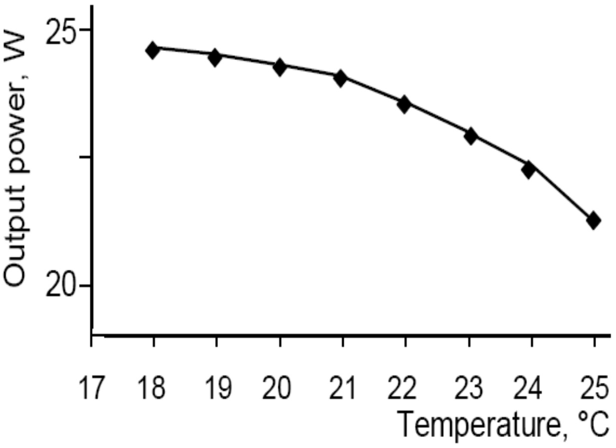

Fig. 4. Output power versus temperature of the diode module base plate.

The dependence of the output power on temperature of the diode module base plate was measured (Fig. 4). With rise of temperature a monotonous decrease in laser output power was observed. This is due to lower efficiency of laser diode at elevated temperature of heterostructure but mainly is caused by the wavelength mismatch between fiber absorption and diode emission bands due to 0.3 nm/°C shift of the diode wavelength towards lower energies. Application of thermoelectric cooling system with temperature repeatability $\leq$ 0.1 ºC ensures stable temperature regime of pumping laser diodes and absence of unwanted oscillations of laser output power.

It is further planned to optimize the cavity parameters in order to increase the output power.

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