A new basic structure suitable for a fully integrated all-fiber-optic stimulated emission dye source

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Abstract. In the present work, our research is focused on an innovative compact all-fiber-optic structure suitable for the development of fully integrated dye lasers. The structure is based on a standard fiber-optic glass ferrule with two parallel openings along its length with diameters of 125 μm. A Fabry-Perot cavity is formed in one of the openings using two fused silica optical fibers with flat end facets. An angle-polished optical fiber with a reflective metal coating is placed in the second opening through which the active medium is pumped transversely. The active medium used is the Rhodamine 6G dye dissolved in glycerine, which is pumped by the 337.1-nm wavelength laser pulses of a nitrogen TEA laser. The ferrule-based design allows for a simplified set-up procedure and the integration of the pumping system to the basic structure of the laser, thus making it very compact. The design of the light source presented allows its future use in applications, such as lab-on-a-fiber, lab-on-a-chip and total analysis micro systems.

1. Introduction

The evolution of opto-fluidic technologies by matching microfluidics with optics opens up opportunities of creating more functional and more compact appliances [1]. The classical biochemical analyses are normally associated with costly and bulky optical elements precisely connected by microfluidic systems. The miniature opto-fluidic light sources compatible with optical waveguides can overcome these restrictions and allow portability of the device. Simultaneously with broad-band light sources based on organic dyes for microfluidic systems, dye lasers are being developed such as ones with micro-ring resonators [2], distributed feedback resonators [3] or based on Fabry–Perot (FP) resonators [4–9].
The miniature lasers with an FP resonator commonly use a microchip created of polydimethylsiloxane for a basic design. The FP cavity in this case is made by two aligned optical fibers with reflective metal coatings on their facets placed into slots in the basic structure or with reflective coatings onto the two ends of a microchannel [5-9]. Another choice for a basic structure is a glass capillary in which two optical fibers are placed, which are aligned using micro-positioners [4]. A microfluidic laser with an FP resonator was also presented, in which the feedback is implemented via Fresnel reflections from the optical fiber facets [10].

In this article we demonstrate a miniature all-fiber-optic structure that has not been previously reported for transversely pumped dye lasers with FP resonators and is also suitable for the development of fully integrated dye lasers. The basic design used in our experiments allows much easier placement and co-axing of the optical fibers that form the resonator compared to the constructions reported so far [4-9]. Experiments were performed with an external pumping source to test the main structure, followed by pumping through an angle-polished optical fiber integrated in the main structure.

2. Experimental details

2.1. Experimental set-up and basic structure used

For the main structure of the light source we used a glass ferrule that is a standard fiber-optic component. It is a glass cylinder with a 2.3-mm outside diameter, a 10.4-mm length and two parallel 125-µm holes along its length. A section of the ferrule with a length approximately of 1 mm is machine-carved to provide access to the two capillary openings. The ferrule mounted in the holder is fixed to a micro-positioner having three linear displacements and two tilts, and then placed under optical microscope observation for mounting and adjustment of the other components of the set-up. A schematic view of the experimental set-up with the components used is presented in figure 1.

Figure 1. Schematic view of the experimental set-up using an external pumping source.

2.2. Active medium

The active medium used is Rhodamine 6G (R6G) dissolved in glycerine with dye concentration of 1.19×10⁻⁴ M. The R6G laser dye and glycerine are of 99.89% purity. A drop of the prepared solution is used to fill the machine-made gap in the ferrule.

2.3. Pumping and receiving components

In the first experiment, a nitrogen TEA laser emitting light pulses at the wavelength λₚ = 337 nm is used as the external pump source for the dye solution. The pump light is focused by a microscope objective (6.3/0.16) to excite the active medium transversely to the optical axis of the resonator, figure 1.
Figure 2. Schematic view of the experimental set-up using an integrated pumping source. (a) A side view of the ferrule used showing the optical fibers that form the resonator, the area is marked of the pumping spot from the pumping fiber (b) a rotated side view of the ferrule used showing the resonator fibers and the pumping fiber.

In the second experiment, the light from the nitrogen laser is introduced into the pumping fiber by a microscope objective (6.3/0.16) placed in one of the holes to excite the active medium transversely to the optical axis of the resonator, figure 2. The pumping fiber has 105 μm/125 μm core/cladding diameters and a facet angle-polished at 45° with a deposited thin aluminium film acting as a micro mirror.

Two fused-silica step-index optical fibers with 105 μm/125 μm core/cladding diameters are placed manually in one of the holes of the ferrule, so that their ends are immersed in the dye solution. The facets of the fibers are made flat using a FibrMet polishing machine for optical fibers. The polishing comprises four stages using four standard diamond polishing papers with a decreasing size of the grains, respectively 30 μm, 9 μm, 3 μm and 1 μm. The fibers thus mounted form an FP resonator, one of which, denoted as the receiving fiber, guides the output signal $\lambda_S$ to a spectrometer, (figure 1 and figure 2). The optical feedback is provided by Fresnel reflections from the air/silica boundary surfaces thus achieving ~4% light reflection at each interface.

Figure 3. Schematic view of the spectrometer scheme used.

A digital camera-based spectrometer is used for the spectral observation of the output signal from the light source. It is composed of a receiving fiber (entrance slit), a ball lens (collimating lens), a transmission diffraction grating (1350 lines/mm) and a computer connected digital camera, figure 3.
an attempt to obtain a strong signal for the spectrometer, a fiber with a large core diameter is used, which compromises the resolution. Thus, the spectral resolution of the spectrometer used is 3 nm.

3. Results

The objective of the present work is to only demonstrate the main design characteristics and advantages of the structure studied, rather than carry out a comprehensive study of the characteristics of the output signal. With the experimental set-ups thus assembled, we observed amplified spontaneous emission (ASE) around 560 nm; one such spectrum is presented in figure 4, together with the fluorescence spectrum of the active medium used and the molar extinction of R6G dissolved in ethanol [11].

![Normalized fluorescence emission spectrum, molar extinction of R6G and the ASE spectrum obtained by using the scheme from Figure 2.](image)

**Figure 4.** Normalized fluorescence emission spectrum, molar extinction of R6G and the ASE spectrum obtained by using the scheme from Figure 2.

To assess the spectral characteristics of the resulting output spectra, we compared them with the spectrum of a CW DPSS laser obtained by means of the spectrometer scheme in figure 3 using an optical fiber with a 105-μm core diameter. The spectra are shown in figure 5, where the laser output spectrum from the DPSS laser before detector saturation can be seen in figure 5 (a). A laser line is detected not only at 532 nm, but also at 808 nm. This is due to the lack of a filter removing the pumping laser diode emission at 808 nm that is not absorbed completely by the active medium of the DPSS laser. Figures 5 (b) and (c) present normalized spectra respectively of the 808-nm line (FWHM of 10 nm) and the 532 nm line (FWHM of 8 nm) of the DPSS laser. The spectra are so broad partly due to the 3-nm spectral resolution of the spectrometer scheme used, as explained above. Moreover, in the present case, both the pumping laser diode and the DPSS laser are multimode, emitting multiple laser lines with a FWHM of a few pm in a spectral range of the order of a few nm. Thus, the observed radiations with maximums at 532 nm and 808 nm appear to be strongly broadened single laser lines.
The normalized output spectra around 560 nm with FWHM of 13 nm and 10 nm are shown in figures 5 (d) and (e), respectively. We consider that the resulting linewidths are comparable to those of the 808 nm and 532 nm laser lines, and that the distortions of the output spectral profiles are due to the low sensitivity of the image sensor used for spectral observation. For a fiber core with a diameter $d = 105 \, \mu m$ and a numerical aperture $NA = 0.22$ and for a wavelength of $\lambda = 560 \, nm$, the number of allowed transverse modes $M > 8000$ is calculated by:

$$M = 0.5 \times \left( \frac{\pi \times d}{\lambda} \times NA \right)^2 \quad (1)$$

Thus, a highly multimode laser is to be expected. For a cavity length of a few tens of centimeters and for the refractive index of the active medium, a longitudinal mode spectral separation of about a few picometers for a single transverse mode can be expected. At the spectral resolution of 3 nm of the spectrometer scheme used, the individual longitudinal modes cannot be distinguished. Taking this into account, we assume that the broadening is due to the multimode nature of the experimental set-up. Acquiring more precise and detailed data on the output characteristics of the miniature light source studied necessitates additional studies using more sensitive scientific instruments.

Selecting a fiber-optic ferrule for the basic design made the process of aligning the optical fibers used for the laser cavity much easier compared to previous design solutions of miniature optical-fiber-compatible transversely pumped lasers [4-9]. In our case, the alignment is done manually, without the need of micro-positioners or fasteners to maintain the alignment, as described in [4]. Consequently, the entire procedure of building and managing the laser is simplified, making the device much more practical in terms of portability and price.

Compared to other types of transversely excited miniature lasers made from polydimethylsiloxane, the main design selected by us has an advantage in what concerns the technological process of production. There is no need to fabricate special slots for placing and fixing the optical fibers because
the ferrule openings are pre-made with a precision of the order of factory tolerances. The only technological process that needs to be performed is machine-carving the section of the ferrule that provides access to the two capillary openings for the laser medium.

4. Conclusions
The design chosen simplifies and facilitates the process of mounting and aligning optical fibers because of the use of a standard fiber-optic component. Further, the design involves the use of an angle-polished optical fiber with a reflective metal layer applied onto the facet to implement transverse pumping of the active medium. The pumping system thus becomes an integral part of the main construction, which has not so far been reported for transversely excited miniature lasers with an FP resonator [4-9]. Additional studies are planned of this design using a pulse-modulated laser diode as a pump source.

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