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Parallel broadband fluorescent light source for optical coherence tomography

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Abstract: We present a new light source for parallel OCT based on multiple waveguides written in Ti:sapphire. Each channel can generate a spectrum of 174 nm bandwidth centered at 772 nm, with an optical power on sample of 30 uW. A system depth resolution of 1.9 um is obtained, which correspond to 1.5 um in tissue.

1. Introduction

Optical coherence tomography (OCT) is a recent technique for biomedical imaging [1]. The longitudinal resolution of such instruments is inversely proportional to the optical bandwidth of the light source. Tomographic images with micrometer resolution have been demonstrated using fiber interferometers with broadband light sources. Femtosecond Ti:sapphire lasers have, therefore, been used as large-bandwidth, high-brightness light sources, and sub-cellular imaging with longitudinal resolution of ~1 μm has been demonstrated in this way. Unfortunately, the complexity and cost of such systems are limiting factors for their widespread use.

Broadband luminescence from Ti:sapphire with luminescence gain bandwidths ranging from 670-1100 nm can also significantly improve the longitudinal resolution to <2 μm, while avoiding the complexity of femtosecond light sources. Ultrahigh-resolution OCT imaging in tissue was performed with such a light source at low speed on an African frog (Xenopus laevis) tadpole in vivo [2].

The brightness of such broadband light sources has been improved by luminescence guiding in channel waveguides fabricated by pulsed laser deposition and subsequent reactive ion etching or Ar ion milling and transverse fundamental-mode luminescence output of several hundreds of μW was achieved [3].

In this paper, we have parallelized such a Ti:sapphire channel-waveguide emitter by structuring parallel ribs into a planar waveguide and pumping these ribs simultaneously by creating an Ar+-laser line focus and coupling this pump light through a cylindrical lens (active in the vertical direction) and a cylindrical microlens array (active in the horizontal direction), thus creating broadband luminescence output in parallel channels. We present parallel OCT using such a light source in a free-space Michelson interferometer with a reflective sample. More experimental results with this parallel system will be reported at the conference.

2. Experimental Set-up

Figure 1 shows a schematic of the experimental setup. The 2W output of an Ar^+ laser operating at 488 nm is used to pump the Ti:Sapphire waveguides. Coupling is realized by focusing the pump beam in a line parallel to the incident face of the crystal by using a 22 mm focal length cylindrical lens, and by focusing the pump beam in the other transverse direction using an array of quartz cylindrical microlenses L2, placed in front of the crystal, with f = 238 um, a 0.12-numerical aperture and a 60 um pitch, which corresponds to the waveguide separation. The Ti:sapphire crystal is mounted on a water cooled holder to maintain its temperature at 15 degrees. The rib waveguides were fabricated by pulsed laser deposition (PLD) followed by photolithography and Ar^+ ion beam etching They were produced in arrays each containing 20 ribs with 3.5 μm depth and 16 μm width separated by 60 μm.

The light from the waveguide outputs is coupled into a free-space Michelson interferometer by means of a custom designed achromatic lens L3 with focal length of 35 mm. An OG 550 optical filter is inserted in front of L3 to prevent the residual pump light to propagate in the system. The broadband beam is divided into the two arms of the interferometer by a 50/50 beamsplitter (BS). One arm of the interferometer is directed to a mirror (M1), which is used as a sample for characterization purposes, and the other leads to a reference mirror (M2) mounted on a voice coil scanner that is driven with a 12.5 Hz symmetric sawtooth voltage. This depth scan system is capable of providing a scan range of 2 mm at an average speed of v = 50 mm/s. Video rate is achieved by acquiring the signal on the

forward and backward move of the reference mirror. The lenses L4 and L5, with focal lengths of 40 mm, are adjusted so that imaging of the waveguide outputs onto the mirrors M1 and M2, respectively is achieved. Dispersion is matched in the two arms of the interferometer in order to maintain resolution. The light reflected from the sample and from the reference mirror is recombined at the same beamsplitter and coupled into a 200-um core-diameter optical fiber MF by means of lens L6 with a focal length of 100 mm. The magnification, which is set by the ratio of L6 over L3 corresponds to coupling the light from one waveguide only. The optical fiber is moved transversely to record the signal from the channels. The two reflected light beams interfere only when the sample and the reference optical path lengths are equal to the coherence length of the source. Uniform scanning of the reference path length results in a constant Doppler shift of the frequency of the light from the reference arm and in a modulation of the interference signal of the two recombined beams at a Doppler frequency of 122 kHz. The optical OCT signal is detected at the output of the 200-um core-diameter fiber by a silicon photodiode. The signal is then amplified and displayed on an oscilloscope. No signal processing is performed for this experiment. A CCD camera is used to image the waveguide outputs for alignment help purposes, by means of a pellicle beamsplitter (PBS) and a lens L7 with a focal length of 250 mm.

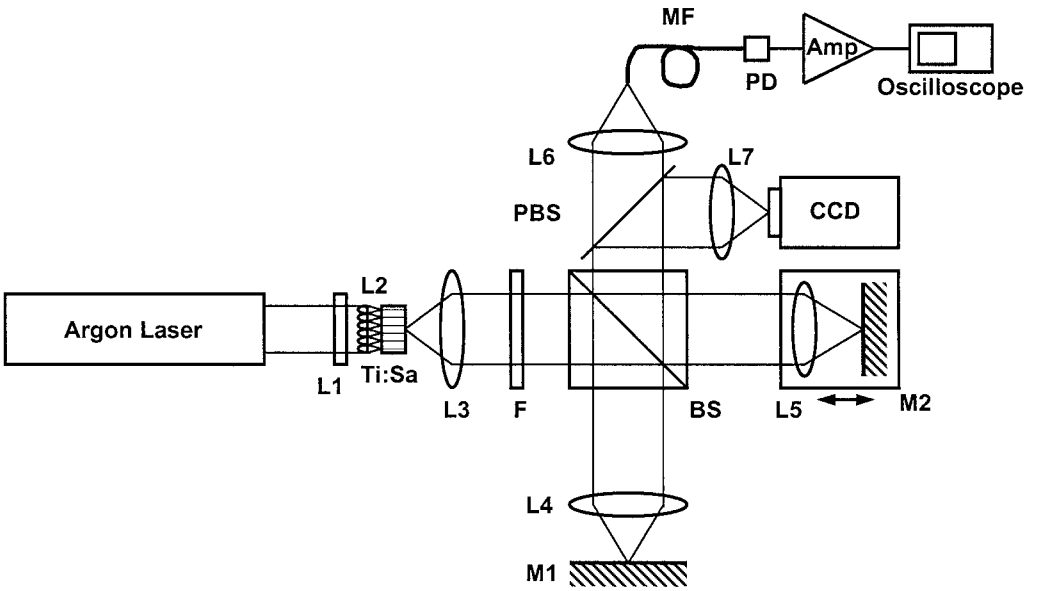


Fig. 1: Parallel OCT system using Ti:Sapphire rib waveguides as broadband fluorescence light sources. L1: cylindrical lens; L2: cylindrical lens array; L3-L7: chromatically corrected doublets; F: OG 550 filter BS: beamsplitter; M1, M2: mirrors; PBS: pellicle beamspliter; PD: photodiode; Amp: amplifier.

3. Results

Figure 2 shows an image of the waveguide outputs. In this experimental setup, sixteen of the twenty waveguides could be excited. The fluorescence intensity profiles obtained at the waveguide output indicate that the rib are able of producing strong optical confinement, however, the fluorescence generated in the areas between the guides has also a non-negligible contribution to the total output. This contribution is attributed to a certain extent to the numerical aperture of the cylindrical microlens array that does not fit exactly the acceptance angle of the waveguides and can be significantly reduced by using a more appropriate microlens array.

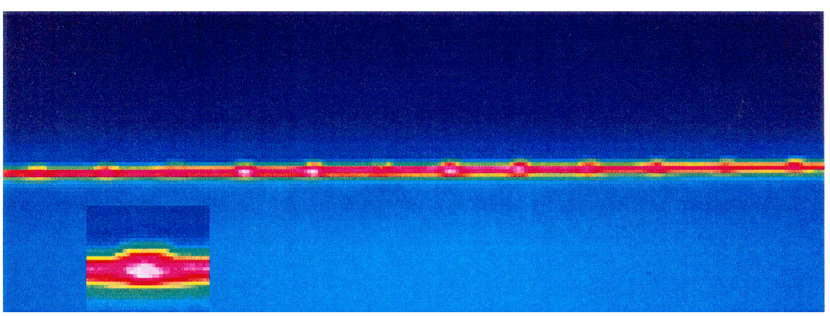
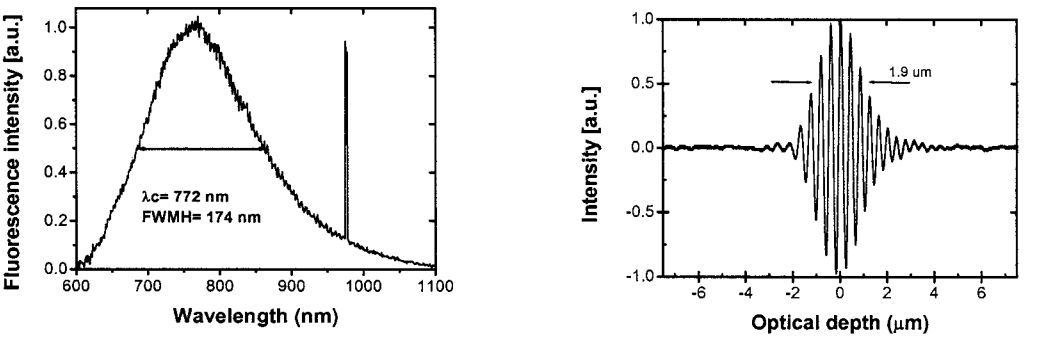


Fig. 2: Waveguide fluorescence output, with a detail view of one channel. The ribs are separated by 60 um. The pump is coupled into the waveguides using a cylindrical lens and a cylindrical microlens array.

A typical optical spectrum generated by one of these waveguide is shown in Fig. 3a. Fluorescence emission centered at 772 nm with a bandwidth of 174 nm was observed. We note that this bandwidth corresponds to a theoretical axial resolution of 1.5 um. The peak located at 976 nm corresponds to the second order of the pump wavelength detected by the spectrum analyser. A total optical power of 470 uW has been measured at the sample surface, which in turn corresponds to an output power of 30 uW per channel. We note though that since there is a contribution to the fluorescence output by the areas between the channel structures, the actual power generated by each of these rib waveguides is slightly lower than this figure. However, we expect that by improving the coupling of the pump light into the ribs their fluorescence output can be significantly increased.

Figure 3b shows an OCT signal from one channel acquired at 25 depth scan per second, i.e. frame per second. For this measurement, the whole 2-W pump power was coupled into one waveguide. Further measurements on the parallel pumping of the ribs are in progress and results will be presented at the conference. The depth resolution of the system was measured to be 1.9 um in the air, which corresponds to a value of 1.5 um in the tissue. The discrepancy from the theoretically predicted resolution value in the air (1.5 um) is likely due to the imperfect match of the dispersion between the arms of the interferometer. It may also result from the pumping power used for the OCT signal acquisition, which was higher than the one employed for the spectrum recording.



(a) (b)

Fig 3: (a) Spectrum at the output of one waveguide. (b) Interferometric OCT signal and measurement of the axial resolution.

4. Conclusion

We have presented a new light source for ultrahigh resolution parallel OCT based on Ti:sapphire rib waveguides. Sixteen parallel channels could generate fluorescence centred at 772 nm with a bandwidth of 174 nm. System resolution of 1.9 um is achieved per channel, with an optical power of around 30 uW on sample per waveguide. This power per channel, which seems quite low for realtime high sensitivity standard OCT, is actually in the right range for video rate parallel OCT with a sensitivity of 90 dB.

References

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