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Flexible Generation of Picosecond Laser Pulses in the Infrared and Green Spectral Range by Gain-Switching of Semiconductor Lasers

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Chapter 1

Introduction

When Theodore Maiman demonstrated the first laser in 1960 [1], the device was famously called "a solution looking for a problem" by his assistant Irnee D'Haenens. Since then, lasers have been developed at a multitude of wavelengths and power levels, and plenty of applications have been found, each requiring specific laser parameters. Often, the improvements of laser sources and applications have gone hand in hand, and the development of tailored light sources is an important direction of industrial and academic research even today.

The requirements of different applications vary greatly. Material processing, for example, demands high power density at low thermal load – this is typically realized via pulsed laser sources with a peak power of at least several kilowatts and a low duty cycle. A high beam quality is required in order to achieve a tight focus on the work piece [2]. Telecommunications, on the other hand, works with low average powers in the milliwatt range, but the transmission of ever increasing data rates requires lasers with stable and narrow wavelength spectra and very high modulation frequencies [3]. Another important application of lasers is in analysis and sensing. This encompasses a variety of methods, such as evanescent sensing of trace gasses [4] or the measurement of velocities, for example in road traffic [5].

The goal of this thesis is in the development of a pulsed laser source for time-domain fluorescence lifetime spectroscopy [6, 7]. In this method, a picosecond pulsed laser is used to excite fluorescence in biological samples. In combination with a fast and sensitive single photon counting system, this allows the measurement of the fluorescence decay lifetime, which is on the order of a few nanoseconds. For many fluorophores, this lifetime depends on properties of the molecule's environment, such as pH-value or Na^{2+} concentration [8]. In general, fluorescence lifetime spectroscopy allows the real-time monitoring of biological processes in living cells.

In order to add spatial resolution, the excitation light is often directed onto the sample through a confocal microscope, which at the same time is used to

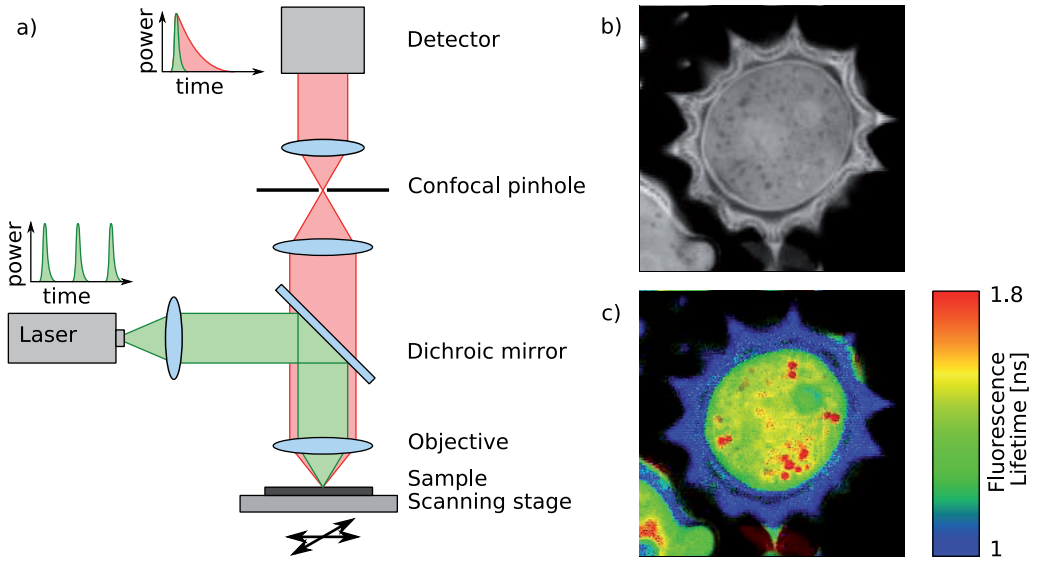

Figure 1.1: a) Confocal fluorescence microscope setup. b) Fluorescence intensity image and c) fluorescence lifetime image of a daisy pollen. The chloroplasts are visible only in the lifetime image (red) but not in the intensity image. Fluorescence images courtesy of PicoQuant GmbH.

collect the fluorescence signal (Fig. 1.1 a). A two-dimensional fluorescence lifetime image can be generated by scanning the probe relative to the beam. Compared to light microscopy or fluorescence intensity microscopy using continuous excitation, fluorescence lifetime imaging microscopy (FLIM) offers enhanced image contrast and the possibility to directly measure biological parameters [6] (Fig. 1.1 b and c).

A related method, Förster resonant energy transfer (FRET) involves energy transfer between two fluorophores. This enables the measurement of distances between single molecules on the nanometer scale, and thus allows the monitoring of molecular interactions [9]. It has been applied, for example, in order to determine the molecular mechanism of muscle contraction [10].

For optimum fluorescence lifetime measurements, the excitation pulse length has to be much shorter than the fluorescence decay time, typically below 200 ps, while the pulse intervals have to be much larger. In order to adjust the repetition rate to different lifetimes and to avoid damaging the sample by excessive illumination, variable excitation pulse repetition rates in the megahertz range are preferred [7]. For advanced methods, like pulse-interleaved excitation [11], freely triggerable excitation pulses are needed. Required pulse energies are between 20 and 100 pJ.

Since the fluorescence has to be detected in the intervals between the excitation pulses, a high extinction ratio of typically above 40 dB is required in order to remain below the dark count rate of the detector.

Laser pulses meeting these specifications can be readily provided in the red and blue spectral range using single gain switched laser diodes [12]. However, so far, no systematic study of the parameter-dependence of the gain switching behavior exists, especially for narrow-linewidth laser diodes. Furthermore, the generation of green picosecond pulses requires a more complex setup, including the frequency-doubling of a gain switched infrared laser diode.

In this thesis, the gain switching behavior of single distributed feedback lasers is studied and the laser diode design is optimized for the generation of particularly intense narrow-band picosecond pulses. In a second step, these will be optically amplified and converted into the green spectral range. Different technologies and miniaturized setups are evaluated. The peak power of the resulting green picosecond pulses surpasses that of previous realizations with flexible repetition rate by an order of magnitude.