Voltage-controlled intracavity THz generator for self-starting Ti:Sapphire lasers

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Abstract: A new scheme for the intracavity generation of terahertz radiation in femtosecond mode-locked Ti:Sapphire lasers is presented. The scheme combines advantages of a fast saturable semiconductor Bragg mirror with that of a photoconductive THz emitter. It significantly increases the efficiency of the intracavity THz generation. In addition, the output THz radiation can be electrically modulated at frequencies up to 100 kHz.

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The generation of THz radiation within a femtosecond mode-locked laser cavity was recently demonstrated [1]. A saturable Bragg reflector (SBR) with a single quantum well (SQW) as a saturable absorber was employed. The radiation was generated by means of quantum beats in the quantum well. More efficient intracavity THz generation was obtained when the SQW structure and later InAs were subjected to a static magnetic field [2,3], but the maximum average THz power generated by these emitters was just 0.8 μW. The output THz power of these emitters can only be controlled by changing the intracavity optical power or the applied magnetic field. Moreover, the modulation frequency cannot exceed several Hertz when a magnetic field is used. Alternatively, photoconducting antenna emitters have been demonstrated to be very powerful THz generators [4] and the THz output power modulation capability, although not demonstrated yet, is an inherent property of this type of THz emitters.

This paper presents a new type of intracavity THz generator which consists of a SBR with an additional photoconductive GaAs layer. Compared to previous schemes the THz emission efficiency is significantly increased in this type of emitters. In addition, a new degree of freedom is added to the intracavity THz emitter because the THz output power can be electrically modulated independently from the laser operation.

A saturable Bragg mirror utilizes a SQW as an optically saturable absorption element in order to start and stabilize mode-locking. Therefore, a part of the energy of each ultrashort optical pulse is lost in the SBR. The absorbed energy can be partially used to generate THz radiation [1]. However, intracavity THz emitters using SQWs showed only limited performance in terms of the THz output power. We propose to employ a low-temperature molecular beam epitaxy grown (LT) GaAs as an alternative to the SQW as a saturable absorber [5] and as THz emitter [6] simultaneously. The THz radiation in the LT GaAs layer is generated by photocarriers which are accelerated in the electric field that is applied between two contacts on the LT GaAs layer [6]. The LT GaAs layer thickness and the strength of the electric field determine the power of generated THz radiation, hence the output THz power can be voltage controlled and even modulated in the time domain.

The voltage-controlled intracavity THz emitter we present comprises a Bragg mirror stack and a LT GaAs layer [7]. The Bragg mirror stack is made of AlGaAs/AlAs layers grown by molecular beam epitaxy (MBE) on a highly resistive GaAs substrate. The LT GaAs layer was grown subsequently onto the Bragg mirror stack at 220 ^{o}C (thermocouple readings) and after the growth annealed *in-situ* in the MBE chamber at 600 ^{o}C for 10 minutes. The electrical contacts to the LT GaAs layer were fabricated by photolithographical patterning of Ti/Au layers and had the shape of parallel metallic stripes of 20 μm width and 50 μm separation. The processed emitter structure was mounted onto a highly resistive silicon substrate. To form an emitter unit a silicon hemispherical lens is attached to its back. The emitter unit was placed into the cavity of an ultrafast mode-locked Ti:Sapphire laser (Femtolasers Produktions GmbH) as an end mirror (Fig.1) and the intracavity laser beam was focused onto the gap between the electrical contacts on the LT GaAs layer. The THz emitter element ensures self-starting of the mode-locking while the InAs intracavity THz generators require additional self-starting elements [3]. A typical spectrum of the laser pulse is shown in the Fig.1. The spectrum has a center wavelength of 826 nm at a spectral width of 16 nm (FWHM).

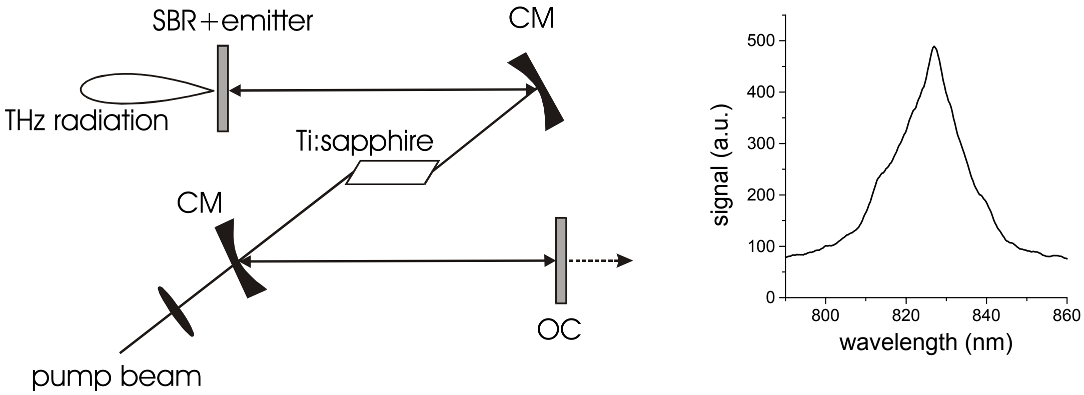

Fig. 1. Schematic of the femtosecond mode-locked Ti:sapphire laser system with LT/SBR THz emitter element: CM's, curved mirrors; OC, output coupler; SBR+emitter, saturable Bragg mirror with THz emitter. The right panel: a typical pulse spectrum

The generated THz radiation was collected by an off-axis parabolic mirror and focused onto a detector. We used a 1 mm thick ZnTe crystal for electro-optic detection of the coherent terahertz radiation [8]. Fig. 2 presents a typical power spectrum of the terahertz transient (see inset in Fig. 2) measured at a bias of 80 V and at an average intracavity optical power of 900 mW. The experimental set-up was not purged with dry nitrogen. Therefore, several absorption lines of water vapor are visible in the spectrum. The THz emission spectrum has a maximum at about 0.3 THz with frequencies components extending beyond 2 THz.

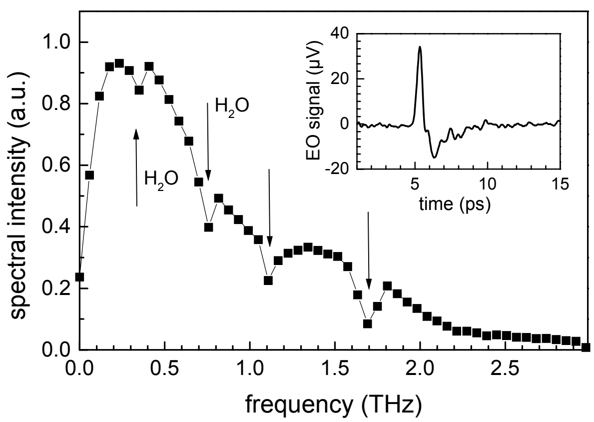

Fig 2. Spectrum of the THz radiation of the LT/SBR emitter. The inset: a typical form of the THz transient.

The maximum amplitude of the electric field of the THz transients scaled linearly with bias up to 110 V (Fig.3a) above which electrical breakdown of the emitter was observed. The average THz power should increase quadratically with bias. Fig 3b displays the average THz power measured by a 4.2 K cooled silicon bolometer. In fact, the power increases superlinearly and can be described with the exponent of 1.9. The maximum average THz power generated by this new type of intracavity THz emitter was about 7 μW for an average optical intracavity power of 900 mW. Thus, an enhancement of the efficiency by more than 50 times compared to the previous results is achieved [1-3]. Due to the absence of any saturation effects for the THz generation with increasing bias, we expect even larger THz output powers if the breakdown voltage of the THz emitter is increased.

In addition, we have demonstrated the capability of an LT/SBR THz emitter to modulate the generated THz radiation. We have applied a square-wave bias by switching a high voltage source. The bias pulse width was ~10 μs and the pulse frequency, hence the duty cycle, was changed. Fig. 4 shows the average THz power as a function of the bias duty cycle for a bias amplitude of 100 V. As expected, the power increases linearly with duty cycle, and - for a duty cycle of 50 % - the average THz power reaches about 50 % of its maximum value. This proves that the THz output for this THz emitter can be electrically modulated with frequencies up to 100 kHz.

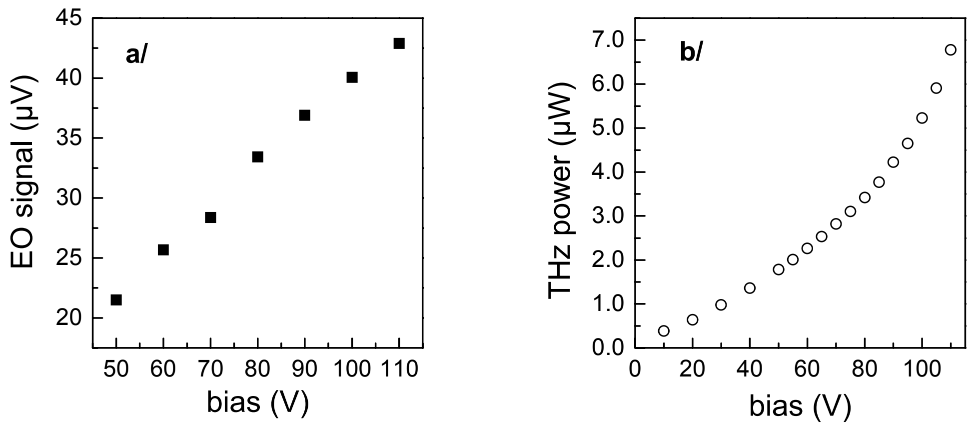

Fig. 3. Electric field of the THz transient (a) and the THz output power (b) as a function of a bias voltage applied to the LT/SBR THz emitter.

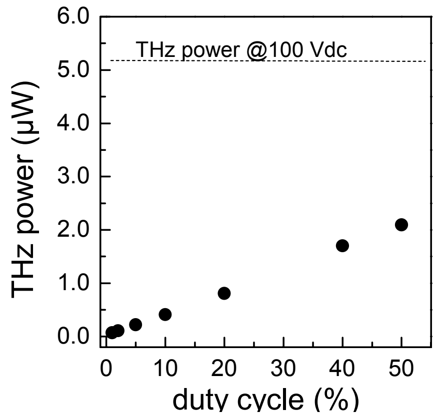

Fig. 4. THz output power as a function of the bias duty cycle. Bias amplitude: 100 V; pulse width: 10 µs.

In conclusion, we have demonstrated a new type of an intracavity THz generator based on a SBR with an additional electrically biased LT GaAs layer. Mode-locking of the Ti:Sapphire laser oscillator with this THz generator element in the cavity is self-starting. The efficiency of the THz emission for this emitter has been increased by more than 50 times compared to previous types of intracavity THz generators. The emitter in the present design has a maximum average THz output power of about 7 µW at an average optical intracavity power of 900 mW. In addition, the THz output power can be modulated in the time domain independently from the laser operation.

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