Intracavity terahertz generation inside a high-energy ultrafast soliton fiber laser

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Intracavity terahertz emission inside a high-energy ultrafast Yb-doped fiber laser is presented. The terahertz radiation is generated by a transient photocurrent induced at the surface of a saturable InGaAs multiquantum well grown by molecular beam epitaxy on top of a semiconductor Bragg reflector. This device simultaneously works as the saturable absorber mirror for initiating and managing the passive mode locking required for the ultrashort pulse operation of the laser system. The maximum terahertz average power achieved is 4.2 μW, which reveals a net conversion efficiency of 3.1×10^{-5}. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3056118]

In recent years, the terahertz frequency range has attracted growing research activities driven by scientific and industrial applications such as defense, security, biology, or medical care. Over the years, different concepts have been developed to increase the available terahertz power and bandwidth.[1–4] The most common ultrashort pulse laser source for terahertz generation and detection was the Ti:sapphire laser operating around 800 nm. In particular for this solid state laser, a few attempts have been made to investigate intralaser terahertz generation in order to take advantage of the intensity enhancement inside the laser cavity. In 1997, Sakura *et al.* presented intracavity generated terahertz radiation using a saturable absorber mirror (SAM) in a folding mirror configuration.[5] The terahertz radiation was generated by quantum beats in a single quantum well layer grown on the Bragg reflector. Three years later, terahertz generation with an InAs wafer as folding mirror was achieved.[6] However, in both cases using the emitter as folding mirror causes terahertz pulse radiation in four different directions. Hence, the amount of applicable terahertz radiation is significantly low. In 2002, Darmo *et al.* investigated an intracavity terahertz emitter based on an electrically biased low-temperature grown GaAs (LT GaAs) layer grown on top of a semiconductor Bragg mirror. Here, in particular, the terahertz emitter also manages the self-starting mode locking of the Ti:sapphire laser. In contrast to the former demonstrated intracavity emitters, the application of an external bias voltage and the improved emission pattern based on a perpendicular excitation increase considerably the IR-to-terahertz conversion efficiency up to 1.5×10^{-5}. Additionally, the processed photoconductive switch can be electrically modulated in the kilohertz regime yielding an enhanced signal to noise ratio for reduced terahertz measuring times in a common terahertz time domain system.[7] Nowadays, the rapid progress in fiber laser technology operating at wavelengths above 1 μm motivates the development of terahertz emitters and detectors that benefit from fiber laser advantages over bulk solid state lasers such as the improved stability, freedom from misalignment and high average power.[8] So far, several investigations of fiber lasers as driving source for the generation and detection of terahertz radiation have been reported.[9–11]

Here, we present intracavity generated terahertz radiation inside a fiber laser. The terahertz emission is based on the excitation of a transient photocurrent at the surface of a saturable Bragg reflector that simultaneously initiates and manages the passive mode locking for the ultrashort pulse operation.

The implementation of a terahertz emitter into a fiber laser cavity involves certain fiber laser characteristics. In particular, here, the generated optical pulses typically propagate through several meters of optical fiber yielding dispersion broadened pulse widths that cannot be applied for efficient terahertz generation. This pulse broadening can be avoided by working in the soliton regime whereby the pulse width undergoes only small changes along the cavity round trip and basically remains its shape through the combined action of group velocity dispersion and Kerr nonlinearity. However, due to the small fiber core size and hence strongly accumulated nonlinearity in standard single mode fibers, the pulse energy is limited due to the soliton area theorem to some tens of picojoules.[12] To obviate this limitation, different approaches of mode locked fiber laser configurations have been demonstrated. For instance, an additional pulse stretching inside the cavity keeps the nonlinear phenomena under control but yields a pronounced pulse breathing per cavity round trip from transform-limited pulses to longer chirped pulses and is therefore not suitable for terahertz generation.[13] Hence, the application of large-mode area (LMA) fibers has been proposed. The enlargement of the active core area significantly reduces nonlinear effects and supports higher pulse energies while only slightly changing pulse widths. We recently demonstrated an Yb-doped fiber laser based on LMA fibers operating in the soliton regime. The output pulse energy was about 16 nJ at 500 fs pulse duration and a repetition rate of about 53 MHz.[14]

In contrast to terahertz generation by Ti:sapphire lasers, GaAs with a bandgap of 1.42 eV cannot be applied for fiber lasers operating above 1 μm. Commonly InGaAs is used and

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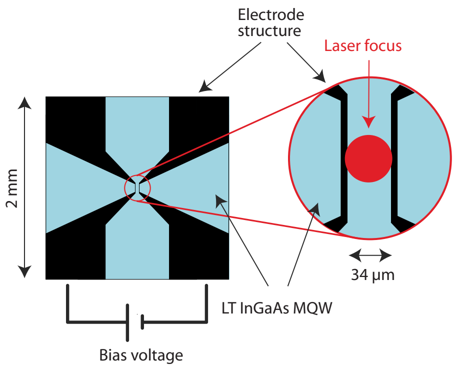

FIG. 1. (Color online) Schematic of the intracavity terahertz-SAM based on an ultrafast photoconductive switch. The Ti/Pt/Au electrodes were processed on a saturable LT InGaAs MQW on top of a Bragg mirror optimized for 1035 nm.

recent studies on specially low-temperature grown InGaAs (LT InGaAs) show promising results as emitter and detector material for terahertz radiation.[15] Hence, for the emitter structure, we processed two Ti/Pt/Au electrodes on a LT InGaAs multiquantum well (MQW). Figure 1 shows the electrode strip lines with a 5 μm electrode width and an active gap of 34 μm. The 26 InGaAs layers with GaAs barriers were grown by molecular beam epitaxy on an AlAs/GaAs Bragg mirror (27 quarter-wave pairs for 1035 nm) which was designed for a reflectance of more than 99%. We set the growth temperature to 300 °C during an arsenic excess to ensure ultrafast recovery times in the range of 1 ps. Including the top quarter-wave GaAs layer of the Bragg mirror the SAM has a resonant design due to an overall optical thickness of seven half-wave layers between the Bragg mirror and the semiconductor surface. The surface including the electrodes was additionally covered with an antireflection coating to increase the supported bandwidth, to decrease the dispersion and to adjust the absorbance to 45%. Moreover the antireflection coating provides the semiconductor with a protection layer which prevents moisture and guarantees higher break through voltages. High electric field strengths are essential for a sufficient charge carrier acceleration to obtain an optimum IR-to-terahertz conversion efficiency. The finalized terahertz-SAM was mounted onto a hyperhemispherical silicon lens to decrease the inward reflected terahertz radiation. Moreover, a hyperhemispherical lens shape has the advantage to radiate the terahertz pulse trains in an increased forward direction. The terahertz-SAM was aligned into the above mentioned high-energy soliton fiber laser as the mode locking device in a sigma-cavity configuration (see Fig. 2). In contrast to a linear cavity design, this setup prevents parasitic effects such as Brillouin scattering during the laser operation yielding an enhanced laser stability. A more detailed description and characterization of this fiber laser can be found in Ref. 14.

During mode locking a fraction of each ultrashort optical pulse is absorbed at the LT InGaAs layer and generates free charge carriers that form an ultrafast surge current induced by the biased electrodes. During acceleration and deceleration the electrons emit electromagnetic pulses in the terahertz frequency range. These pulse trains were collected and directed by two off-axis parabolic mirrors onto another identically fabricated terahertz-SAM as detector, which was triggered by IR pulses coming from the fiber laser output, as

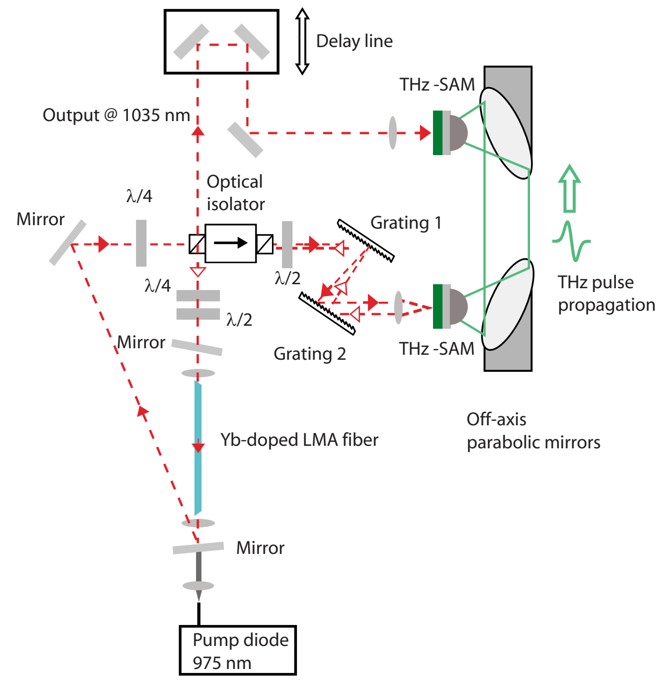

FIG. 2. (Color online) Schematic of the self-starting ultrashort pulse Yb-doped fiber laser combined with the terahertz time domain system based on a terahertz-SAM. The investigated terahertz-SAM has the capability to generate and detect terahertz radiation as well as initiating and managing the mode locking process for ultrafast laser operation.

shown in Fig. 2. The induced signal was amplified and recorded using a lock-in amplifier. The experimental results for terahertz field strength and spectral amplitude can be seen in Fig. 3. Due to the applied IR pulse widths of about 510 fs (see Fig. 4, assuming a sech^2 pulse shape) for terahertz generation and detection the spectral amplitude is limited to below 0.5 THz. In a second step we measured the average tera-

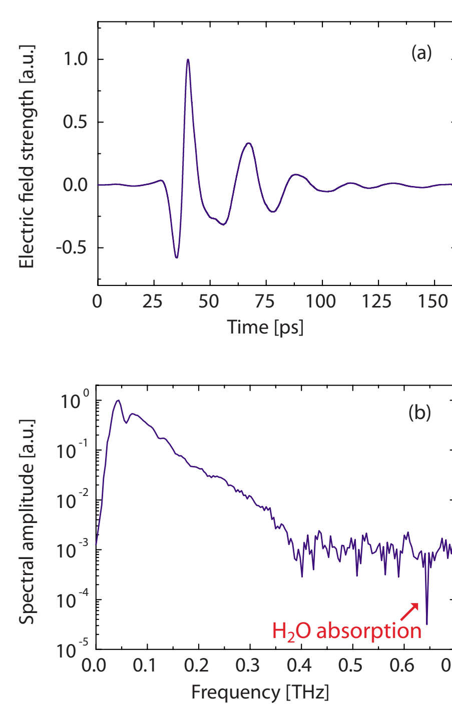

FIG. 3. (Color online) Measured terahertz electric field strength (a) and corresponding spectral amplitude (b) using a terahertz-SAM for generation and another terahertz-SAM for detection.

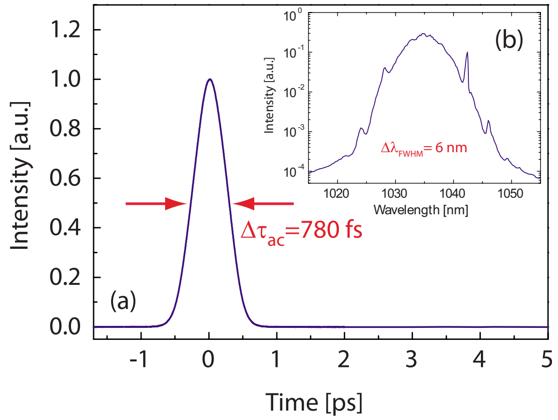

FIG. 4. (Color online) Autocorrelation trace (a) and optical spectrum (b) of the fiber laser pulses during passive mode locking based on the terahertz-SAM. The intracavity average power was estimated to be about 300 mW whereas the provided output power was around 400 mW at 47 MHz repetition rate.

hertz power using a pyroelectric detector on the basis of a $LiTaO_3$ crystal with an active element size of 6 mm^2. The results for the terahertz average power depending on the applied electrical field strength are plotted in Fig. 5. Taking into account a modulation depth of 0.45 at the InGaAs MQW and an incident intracavity power of 300 mW, 135 mW contribute to the terahertz excitation. This corresponds to a maximum IR-to-terahertz conversion efficiency of about $\eta = P_{THz}/P_{IR} \approx 3.1 \times 10^{-5}$. The parabolic dependency on the bias field strength, as shown in Fig. 5, reveals an acceleration of the excited electrons below the saturation velocity which is determined by the saturation electric field strength.[16] The square wave generator used for biasing the terahertz-SAM delivered a maximum peak voltage of 25 V, however, this result promises even enhanced IR-to-terahertz conversion efficiencies at higher electric field strengths.

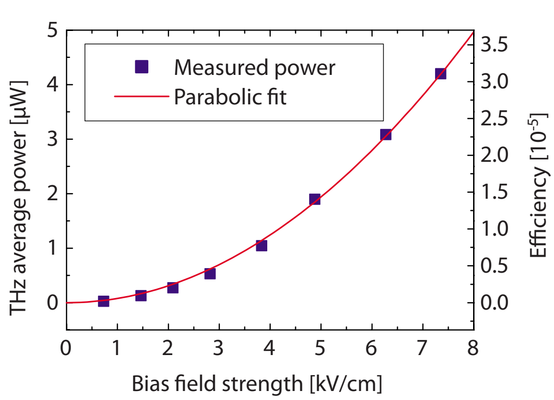

FIG. 5. (Color online) The terahertz average power shows a parabolic dependency on the applied electric field strength E_{bias}. For $E_{bias} \approx 7.4$ kV/cm an average output power of $P_{THz} \approx 4.2$ μW is obtained. Considering a modulation depth of 0.45 at the terahertz-SAM and an incident intracavity power of 300 mW, 135 mW IR average power contribute to the generation of terahertz radiation. This corresponds to an IR-to-terahertz conversion efficiency of $\eta = P_{THz}/P_{IR} \approx 3.1 \times 10^{-5}$.

In conclusion, we demonstrated an intracavity terahertz emitter for fiber lasers. This device is based on an ultrafast photoconductive switch processed on an InGaAs SAM. The fabricated device can be used as terahertz emitter, as terahertz detector and also manages simultaneously a self-starting mode locking operation for solid state lasers working above 1 μm. The maximum achievable terahertz average power can be increased for more powerful laser systems by enlarging the active area of the InGaAs layer or by processing interdigital finger electrode emitters, as demonstrated in Ref. 16. For the generation and detection of higher terahertz frequencies one has to further reduce the IR pulse lengths at the emitter and detector, respectively. This can be achieved by exploiting the dispersion and nonlinearity management of the fiber laser and adjusting the shortest pulse length per cavity round trip exactly at the position of the terahertz-SAM. Recently Tang and Zhao demonstrated 47 fs long pulses directly from an Er-doped fiber laser by optimizing the position of the output coupler.[17] Altogether, the investigated terahertz-SAM demonstrates, due to its multipurpose capabilities, a potential device for future compact, reliable, high-energy, and ultrashort pulse fiber laser systems with an included submillimeter radiation source.

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