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THz Radiation from Intracavity Saturable Bragg Reflector in Magnetic Field with Self-Started Mode-Locking by Strained Saturable Bragg Reflector

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We demonstrate a new configuration for intracavity generation of THz radiation. A magnetic-field-biased saturable Bragg reflector (SBR) located inside the femtosecond laser cavity is the emitter, while a strained saturable Bragg reflector (SSBR) achieves self-started mode-locking without focusing. The calibrated power of the emitted THz radiation is estimated to be approximately 45 nW with a peak frequency at 0.72 THz and width of approximately 0.7 THz under a 0.88 T magnetic field. The quadratic dependence of THz-radiation power by the SBR on the magnetic field is also observed for the first time.

KEYWORDS: THz radiation, intracavity, strained saturable Bragg reflector, low saturation intensity, saturable Bragg reflector, magnetic field

Many materials and devices with femtosecond laser pulse pumping geometry have been proposed and demonstrated to generate THz radiation,[1–4] and it has become a powerful scheme for far-infrared spectroscopy as well as various imaging applications.[5] A saturable Bragg reflector (SBR) has been used to generate strong THz radiation in the intracavity geometry.[6] This scheme takes advantage of the higher optical peak power inside the cavity. However, it is desirable to optimize the mode-locker and intracavity THz emitter separately. Previously, dye saturable absorbers were employed for self-starting mode-locking in these intracavity THz-radiation generation systems.[6,7] However, the systems were bulky and relatively inconvenient to use. Recently, a new type of saturable absorber, the strained saturable Bragg reflector (SSBR), has been successfully developed for self-starting mode-locking with no focusing because of its very low saturation fluence of approximately 7 mJ/cm^2.[8] In this study, we combined these ideas to examine a new type of intracavity THz-radiation generation system. The SSBR allows the construction of a more compact system and facilitates mode-locking of the Ti:sapphire laser with intracavity SBR to generate higher THz-radiation power. On the other hand, a magnetic field can be used not only to switch THz-radiation beams[9] but also to generate larger average THz-radiation power in the extra cavity[10] or intracavity[7] geometries. Here, we also discuss the characteristics of the intra cavity THz-radiation generation system with SBR as a function of magnetic field strength for the first time, to the best of our knowledge.

The intracavity THz-radiation generation system is shown in Fig. 1. The configuration is a modified Z-folded cavity containing a 1-cm-long Ti:sapphire rod, two folding mirrors with 10-cm radius of curvature and a pair of SF11 Brewster prisms separated by 35 cm for the intracavity dispersion compensation. The SSBR is used without focusing as the saturable absorber and the end mirror in the dispersion-compensation arm of the cavity. The structure of the SSBR device has been reported in detail elsewhere.[8] In brief, 15 pairs of high-low $\lambda/4$ layers of AlAs/$\mathrm{Al_{0.25}Ga_{0.75}As}$ were grown as the distributed Bragg reflector (DBR). Three strained quantum wells (QWs) ($\mathrm{In_xAl_{1-x-y}Ga_yAs}$) were inserted into the top layer of the DBR mirror with an additional $\lambda/2$ layer of $\mathrm{Al_{0.25}Ga_{0.75}As}$. The SBR, which serves as the THz emitter[6,7] is in the other arm of the z-folded cavity as the end mirror. Its Bragg reflector consists of 24 pairs of $\mathrm{Al_{0.33}Ga_{0.67}As}$/AlAs $\lambda/4$ layers and a top $\lambda/4$ layer of AlGaAs including a single 10-nm-thick GaAs QW. The SBR is placed at the center of a compact electromagnet which can be tuned from 0 T to approximately 0.88 T. At 10 W pumping power, stable mode-locking was obtained with the laser generating approximately 160 fs pulses at the center wavelength of 800 nm, and a spectral width of 4.8 nm, as shown in Figs. 2(a) and 2(b). These were monitored by using the two leakage beams from the 45-degree high-reflectivity (HR) folding mirror of the laser (see Fig. 1). The average and peak output powers inside the cavity were 8 W and 480 kW, respectively, with a 105 MHz repetition rate. The THz-radiation detection system is the same as that described in our previous work.[6,7] The emitted THz radiation in the transmission direction was guided by the two parabolic mirrors directly to the InSb bolometer for detecting the THz-radiation power or to the Fourier-transform polarizing interferometer for measurement of the THz-radiation spectrum.

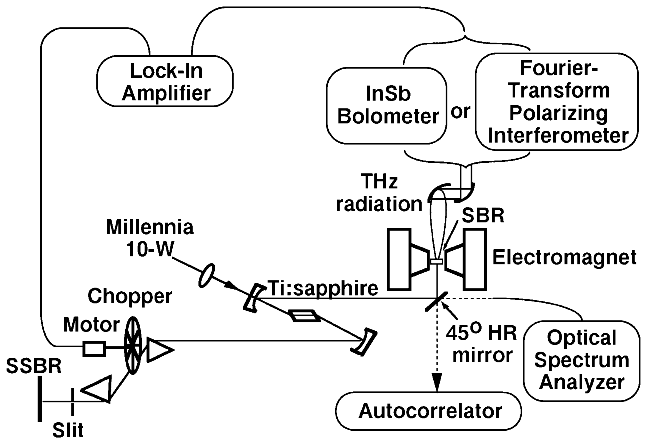

Fig. 1. Experimental setup of a mode-locked laser started by an SSBR without focusing on it and an intracavity SBR in a magnetic field as a THz-radiation emitter.

We observed a quadratic dependence of the THz-radiation power on the magnetic field, as shown in Fig. 3. With a

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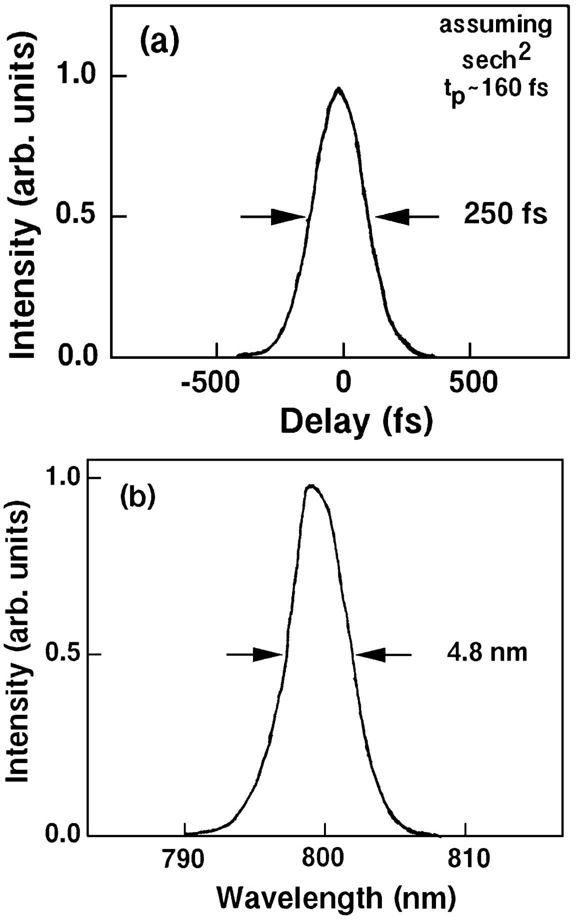

Fig. 2. (a) Autocorrelation trace of 160 fs pulses assuming a sech^2 pulse shape from the mode-locked Ti:sapphire laser with SSBR. (b) Corresponding spectrum of center wavelength and spectral width were approximately 800 nm and 4.8 nm, respectively.

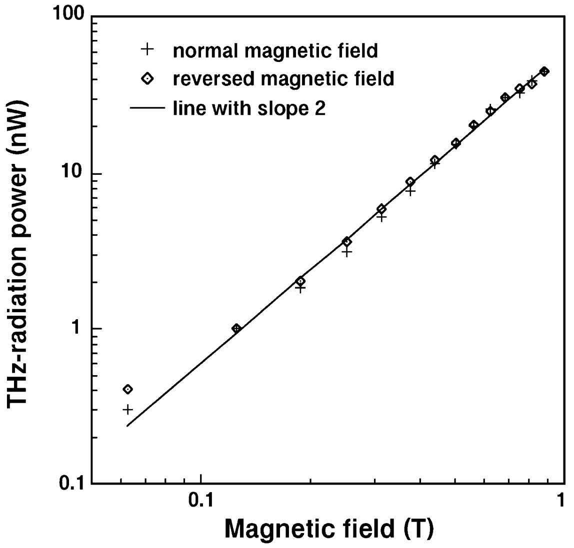

Fig. 3. Quadratic relationship between THz-radiation power and magnetic field with log scale diagram. The cross and the diamond with a dot in the center indicate the opposite polarities of the magnetic field, respectively. The solid line slope is 2.

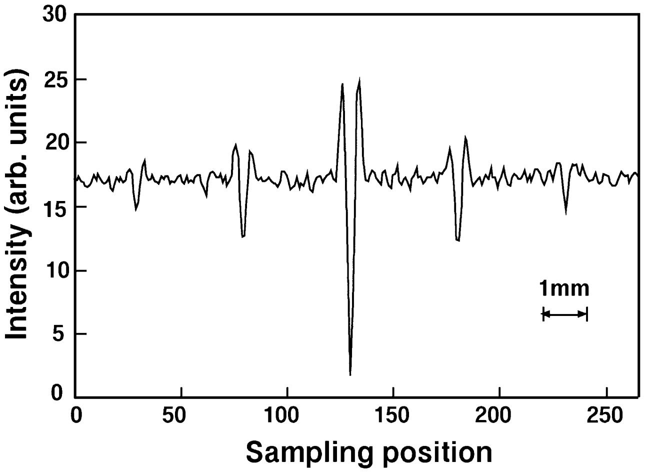

Fig. 4. Autocorrelation interference pattern of the THz-radiation temporal shape from intracavity SBR in a 0.88 T magnetic field obtained by a polarizing Michelson interferometer.

magnetic field of 0.88 T, the observed average THz-radiation power was around 45 nW. This is comparable to that obtained for the system with a dye jet as the mode-locker,[7] and is one order of magnitude larger than the previous intracavity result without a magnetic field (~2–3 nW).[6] This indicates that a magnetic field can strongly modulate the carriers in the SBR to generate a larger amount of THz-radiation power. The quadratic dependence is the same when the polarity of the magnet is reversed. Similar behavior was observed in InAs[10] and GaAs.[9] This is reasonable since reversing the direction of the magnetic field only changes the direction of the dipole, not its magnitude. In comparison, the quadratic magnetic-field dependence is almost exact for the SBR, whereas this dependence is valid for higher magnetic fields only for InAs and GaAs. Without the magnetic field, no radiation was detected in this geometrical configuration. With the wire-grid polarizer, the THz radiation was confirmed to be vertically polarized. The present experiment thus verified that the THz radiation emitted by the SBR is entirely generated and modulated from the magnetic-field effect. No THz radiation was detected by the intracavity SSBR with or without the magnetic field. We have tentatively attributed this to the use of a doped rather than semi-insulating substrate in this SSBR. Further investigation of the difference between the SSBR and SBR in terms of intracavity THz generation is in progress.

Using a polarizing Michelson interferometer, we have measured the electric-field autocorrelation of the THz field from the intracavity SBR in a 0.88 T magnetic field, as shown in Fig. 4. The corresponding spectrum is obtained by Fourier analysis of the interferogram and illustrated in Fig. 5. We believe that the oscillations of the THz radiation spectrum are due to the multiple reflections of THz radiation in the substrate. It is also instructive to compare Fig. 5 with previous intracavity THz generation results.[6,7] The peak THz radiation is around 0.72 THz, which is higher than that without the magnetic field (0.66 THz),[6] but lower than that one with the magnetic field (0.8 THz).[7] This is reasonable because the excitation pulse width also affects the THz-radiation center frequency.[11] With a dye jet as the saturable absorber, the pulse width of the intracavity THz generation system with a laser beam normally incident on the SBR was 130 fs,[7] whereas the same system with a laser beam incident on the SBR at a shallow angle was ~180 fs.[6] Furthermore, the signal-to-noise ratio of the THz spectra is superior. This could be due to the

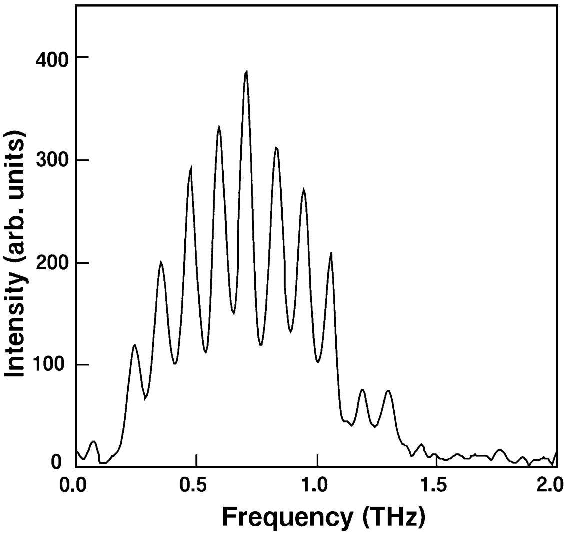

Fig. 5. THz-radiation spectrum from intracavity SBR in a 0.88 T magnetic field obtained by Fourier transformation of the autocorrelation from a polarizing Michelson interferometer.

stronger pulse shortening force of the SSBR and the lower noise of the Ti:sapphire/SSBR laser than the Ti:sapphire/dye laser.[12,13)]

In summary, we have demonstrated a new type of high-power intracavity THz-radiation system with an SBR in the magnetic field as the THz-radiation emitter and an SSBR, which allows construction of a more compact intra-cavity with stable self-starting mode-locking. Biased at 0.88 T, THz radiation with an average power of around 45 nW was generated. Its center frequency and bandwidth were around 0.7 THz. The quadratic dependence of the THz-radiation power on the magnetic field supported the belief that the THz radiation results entirely from the magnetic-field-induced Lorentz force, which accelerates the carriers of SBR. Using this method, it is also possible to achieve still higher THz-radiation power by higher intracavity peak power geometry and larger magnetic field.

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