Generation of tunable dual-wavelength optical short pulses for the generation and modulation of terahertz radiation

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Received December 10, 2010; accepted January 22, 2011; posted online June 27, 2011

A new scheme to realize terahertz (THz) radiation generation, as well as high-speed THz modulation, for future high-speed THz communication systems, is proposed and discussed. The proposed experimental scheme includes two elemental parts: dual-wavelength mode-locking oscillating cavity and photomixing elements. The conditions for double-wavelength operation using the proposed experimental setup have been theoretically discussed and obtained. The mode-locked output optical short pulses with two high-stability wavelengths are obtained and demonstrated. These can be used to produce THz radiation, as well as high-speed signal modulation, through the photomixing effects in an ultrafast oxygen-ion-implanted and epitaxial InGaAs:O for the future high-speed THz communication systems.

OCIS codes: 060.2390, 140.3520, 140.3560.

doi: *10.3788/COL201109.S10205*

Many groups are now developing terahertz (THz) generation and modulation devices, or subsystems with small size and compact structure, for future high-speed wireless THz free-space communication[1−3]. Photomixing is one of the promising THz sources because it is potentially compact, easily integrated, low cost, has low power consumption, and the frequency of the generated THz signal can be easily tuned by adjusting the central frequency of the two or any one of the photomixing pump lasers[4−10]. Usually, the optical sources with a THz difference in their central frequency can be obtained through the use of either two discrete lasers or monolithically integrated laser arrays[11,12]. The two discrete linearly polarized laser beams are then applied to pump the photomixer to generate THz emission[10,13,14]. However, the use of multiple lasers operating at different wavelengths increases the cost and complexity because wavelength drift and output power fluctuation from the variations in the environmental temperature and injection current exist. Therefore, an alternative approach in which multiple lasing wavelengths share a single gain medium may be more attractive[15−17]. The actively mode-locked ring laser is one of the preferred kind of lasers to generate such pulses because of its simple structure, no external cavity requirement, good pulse quality, small timing jitter, and coherence from pulse to pulse[18]. Furthermore, double- or multiple-wavelength operation can also be obtained through the design of a suitable structure of the actively mode-locked ring cavity.

In this letter, a new scheme to realize THz radiation generation, as well as high-speed signal modulation, for future high-speed THz communication systems is proposed and discussed. The proposed experimental scheme includes two elemental parts: dual-wavelength actively mode-locked fiber ring laser and photomixing elements.

The proposed dual-wavelength actively mode-locked ring laser uses a 1.55-μm semiconductor optical amplifier (SOA) acting as both the gain element and the optically controlled mode-locker, and two cascaded fiber Bragg gratings (FBGs) as the wavelength-selecting element. The ring cavity length of this laser is very short, thereby minimizing the impact of environmental perturbation on the laser stability. More importantly, the configuration of this laser is very simple, and the two mode-locked lasing wavelengths can be conveniently tuned by merely adjusting the two cascaded FBGs. Furthermore, the average side-mode suppression ratio (SMSR) achieved in this laser is better than 40 dB.

The experimental setup shown schematically in Fig. 1 includes two elemental parts: the dual-wavelength mode-locking ocsillating cavity and the photomixing elements. The dual-wavelength mode-locking ocsillating cavity is composed of one 1.55-μm SOA, one polarization-independent isolator, one polarization controller (PC), two cascaded FBGs, two optical circulators (OC), one 10:90 coupler, and one optical delay

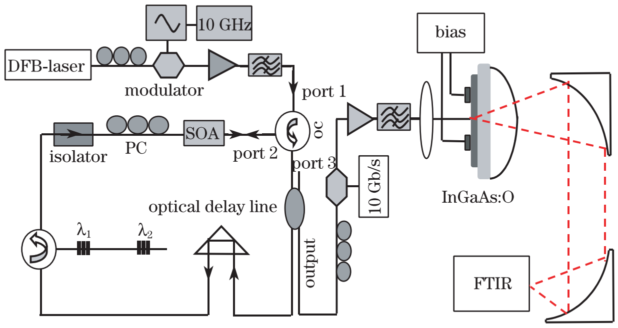

Fig. 1. Experimental setup.

line. The duration of the delay is controlled by adjusting the position of the prism reflector mounted on a translation stage driven by a stepper motor. The stepper motor is controlled by a microprocessor. The variable delay of the delay line can be controlled with a resolution of 0.002 ps and a maximum delay of 170 ps. The SOA has a typical small-signal gain of 25 dB at 150-mA bias and a saturated output power of 3.9 dBm. The peak reflection wavelengths of the FBGs are $\lambda_1 = 1545.35$ nm and $\lambda_2 = 1554.51$ nm, with a peak reflectivity of approximately 95% and a 3-dB bandwidth of 0.19 and 0.21 nm, respectively. The FBG string is connected to the ring cavity through a circulator, and oriented with the shorter wavelengths reflected closer to the ring cavity. The control-mode locking signal is launched into the ring cavity through the other optical circulator, and is blocked by the optical isolator after it passes through the SOA. The optical isolator and circulators ensure the unidirectional operation of the ring laser. The net gain provided by the SOA inside the ring cavity and the matching between the length of the ring cavity, which can be adjusted through the optical delay line, and the modulation frequency of the optical signals, which is fixed at 10 GHz injected into the SOA, determine whether the ring laser can generate pulses. The generated optical pulses with two different wavelengths with THz frequency offset from the ring cavity are then modulated at 10 Gb/s using a lithium niobate Mach-Zehnder modulator. Because the lithium niobate Mach-Zehnder modulator is polarization-dependent, another PC is used before the Mach-Zehnder modulator. After amplification in an erbium-doped fiber amplifier (EDFA), the fiber output is focused onto the InGaAs:O photomixer, which is biased at 1.5 V. The generated THz emission by the photomixer is coupled to free space through a hemispherical Si lens. The THz is then collimated by a parabolic mirror and fed into a Fourier transform infrared spectrometer (FTIR) to observe the modulation spectra.

The principles of two-wavelength lasing using the proposed scheme and the conditions for two-wavelength operation are derived as follows. The mth harmonic mode-locking frequency of the laser cavity can be expressed as

$$f = mc/[n(L + 2kd)], \tag{1}$$

where $k = 0$ and 1, c is the speed of light in vacuum, n is the refractive index of the cavity fiver, d is the spacing between adjacent gratings, and L is the ring cavity length for the first wavelength. From the above equation, the expressions of the mth harmonic frequency of the two wavelengths selected by the gratings are obtained as

$$f^m(\lambda_1) = mc/(nL), \tag{2}$$

$$f^m(\lambda_2) = mc/[n(L + 2d)]. \tag{3}$$

If $L = m \times 2d$, by properly designing the cavity, the $(m+1)$th harmonic frequency of wavelength λ_2 is

$$\begin{aligned} f^{m+1}(\lambda_2) &= (m+1)\,c/[n\,(m \cdot 2d + 2d)] \\ &= mc/nL = f^m(\lambda_1). \end{aligned} \tag{4}$$

Thus, the two wavelengths can be mode-locked simultaneously at the same modulation frequency if an inhomogeneously broadened gain medium, such as the cooled erbium-doped fiber (EDF), is adopted[16], or if a time-spectrum separation technology is used[19]. Here, the SOA used in the proposed scheme can function as an inhomogeneous gain medium and realize lasing in two wavelengths with negligible mode competition.

By adjusting the power of the control light and the bias current of the SOA, stable pulse trains of the two different wavelengths at the repetition frequency of 10 GHz set by the control signal were obtained by carefully tuning the optical delay line and adjusting the polarization control inside the ring cavity. Both spectra and pulse trains can be recorded simultaneously. Figure 2(a) shows the typical mode-locked pulse trains at a repetition frequency of 10 GHz when the SOA, biased at 160 mA, is modulated by the external optical signal at 10 GHz. The pulse width is approximately 19 ps. The pulse peak at 800 ps is higher than the foregoing ones because there is fluctuation in the entire experimental testing process. This kind of fluctuation can be regarded as the random noise of the experimental testing system. Figure 2(b) shows the corresponding optical spectrum of the pulses of the two

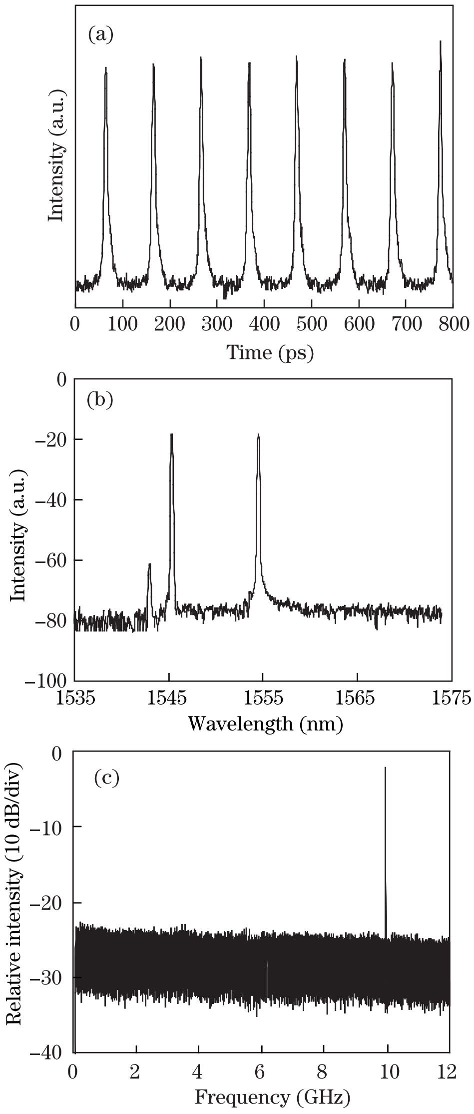

Fig. 2. (a) Mode-locked output pulses at a repetition rate of 10 GHz; (b) the spectrum of the mode-locked output pulses; (c) RF spectrum of the mode-locked output pulses.

oscillating lasing wavelengths. The lasing wavelengths are 1545.35 and 1554.51 nm, with a 3-dB spectral width of approximately 0.29 nm. The average output power is approximately 3.1 mW. The output power can be further increased by changing the SOA driving current and adding one EDFA into the ring cavity to increase the net gain inside the ring cavity. The wavelength tuning of the mode-locked laser can be realized by adjusting the central reflection wavelengths of the two cascaded FBGs. The range of the tuning wavelengths of the ring laser can be extended to cover the whole gain region of the SOA simply by adding additional tunable FBGs to reflect those wavelengths in the remaining gain region. The control optical signal is sinusoidal in shape, and its wavelength is fixed at 1543.03 nm during the experiment only because the wavelength of the DFB laser used in the experiments is fixed during the entire experiment. In fact, the wavelength of the control signals can be changed to any other wavelengths among the whole range of SOA gain spectra if a tunable DFB laser is used. The stability of the output pulse trains was measured via an radio frequency (RF) spectrum analyzer with a fast photodetector. Figure 2(c) shows a typical RF spectrum of the optical pulses. The noise is approximately 20 dB below the lasing signal, indicating that the amplitude of the output pulses is very stable.

The generated optical short pulses can be focused into the InGaAs:O to generate the THz emission through the photomixing effects. Theoretically, the expression of the power of the generated THz wave can be obtained according to the general photomixing theory[3−5], and the related material properties and device structure of the photomixing based on the InGaAs:O.

In conclusion, we propose a new scheme to realize THz radiation generation, as well as high-speed signal modulation, for future high-speed THz communication systems. The principle and detailed analyses of the generation of tunable dual-wavelength mode-locking optical pulses with high stability have been presented. The conditions for double-wavelength operation using the proposed experimental setup have been theoretically discussed and obtained. Very stable mode-locked pulses with two wavelengths at 10 GHz have been obtained using two cascaded FBGs as the wavelength-selecting element and the SOA as both the gain and mode-locking element. Wavelength tuning can be achieved by simply adjusting the central reflection wavelength of the FBGs. The pulse widths of the output-mode-locked pulses at 1545.35 and 1554.51 nm are 19 and 21 ps, respectively. The mode-locked output optical short pulses can be used to produce THz radiation through the photomixing effects in an ultrafast oxygen-ion-implanted and epitaxial InGaAs:O. The high-speed THz modulation in the proposed scheme can be realized through directly transferring the high-frequency data signals in the second Mach-Zehnder modulator onto a THz carrier frequency through the photomixing process in the InGaAs:O photomixer. Thus, the THz modulation rate using the proposed scheme can keep the pace of the modulation bandwidth increase of the optical modulator using optical fiber communication systems. Further research on theoretical analyses and detailed expressions of the power of generation and modulation of THz signals are needed.

This work was supported in part by the National Natural Science Foundation of China under Grant No. 60877059. The authors sincerely thank W. Shi, X. Huang, and Y. Xu at Wuhan Accelink Technologies Co., Ltd., China, and X. Shu at Aston University, UK, for fabricating the fiber Bragg gratings used in the experiments.

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