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Tunable multiterahertz beat signal generation from a two-wavelength laser-diode array

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We report, for the first time to our knowledge, generation of a tunable miltiterahertz modulation signal on an optical carrier directly from a single laser source. The modulation frequency, which can be tuned from 0.15 THz to more than 7 THz, is the beat note obtained by varying the spectral separation between the coaxial two-color output of a two-wavelength laser-diode array from 0.32 to 17 nm. The frequency characteristics of the terahertz beat note are determined with a noncollinear intensity autocorrelator.

An optical beam that is intensity modulated at terahertz rates is desirable for many applications, e.g., wideband optical communication, heterodyne interferometry for absolute distance measurement,[1] four-wave mixing in a laser diode,[2] soliton pulse train generation,[3] and millimeter wave or tetrahertz radiation generation.[4] By recombining a linear chirped optical pulse and its time-delayed replica, Weling *et al.*[4] reported tunable optical quasi-sinusoidal intensity modulation up to ≈ 1 THz but with a duty cycle of less than 0.3%. The bandwidth of the radiated terahertz signal, however, was relatively broad ($\Delta f \approx 36$ GHz). Generation of a modulated signal by direct modulation of a high-speed laser diode or by an external waveguide modulator at 63 GHz (Ref. 5) and 40 GHz,[6] respectively, was achieved. Alternative schemes for optoelectronic generation of a tunable narrow-band millimeter wave signal up to 60 GHz include laser heterodyning or optical mixing of two lasers in metal semiconductor field-effect transitor or HEMT devices.[7] Experimentally, this requires precision alignment of two frequency-stabilized lasers, at least one of which must be broadly tunable.

Phase noise compensation for reduction of the electrical line width of the multigigahertz beat signal has also been shown to be desirable.[8] By selecting only the adjacent two modes and suppressing all other modes in the optical spectrum of a mode-locked laser diode, Novak and Tucker generated a beat note at 37.2 GHz.[9] The optical modulation depth was 100%. The modulation frequency, however, cannot be easily tuned. Recently, Arahira *et al.*[10] demonstrated optical pulse generation from a passively mode-locked laser diode at a repetition rate as high as 1.54 THz. The time-averaged laser spectrum consisted only of three modes separated by 12.5 nm ($\cong$1.5 THz). As a result, the pulse envelope (FWHM $\approx$ 260 fs) was close to sinusoidal, i.e., that of a beat note. Previously, we reported a novel cw tunable two-wavelength laser-diode array (TWLDA).[11] The spectral separation $\Delta\lambda$ of the two-color laser output can be quasi-continuously tuned from 3.52 to 11.29 nm. The output power of the two resonant laser modes was very stable, because these modes used different gain regions of the array. This laser source would thus be an interesting alternative for the applications mentioned above.[1–4] In this Letter we report the generation of a cw intensity-modulated optical beam at what is to our knowledge the highest modulation signal to date, 7 THz, directly from a single laser source. The multiterahertz beat frequency is characterized with a noncollinear autocorrelator.

Figure 1 shows the experimental setup. The configuration of the TWLDA is shown in the inset of Fig. 1. The V-shaped double slit and the end mirror in Ref. 11 are replaced by a V-shaped double-stripe end mirror. The length of each stripe is 15 mm. The angle between the two stripes is approximately 15°. The width of each stripe is 0.167 mm, corresponding to an equivalent spectral filter with a bandwidth of 0.27 nm. This is just smaller than the mode spacing of the diode chip. The spectral separation of the dual-wavelength laser output is determined by the separation of the two stripe mirrors. By vertically moving the stripe mirrors out of or into the plane of the inset of Fig. 1, we can tune the spectral separation of the two wavelengths quasi-continuously from 0.32 to 17 nm in multiples of 0.32 nm, which is the mode spacing of the diode chip. This is shown in Fig. 2. The tuning range of $\Delta\lambda$ is almost twice as large as our previous data.[11] To our knowledge, this

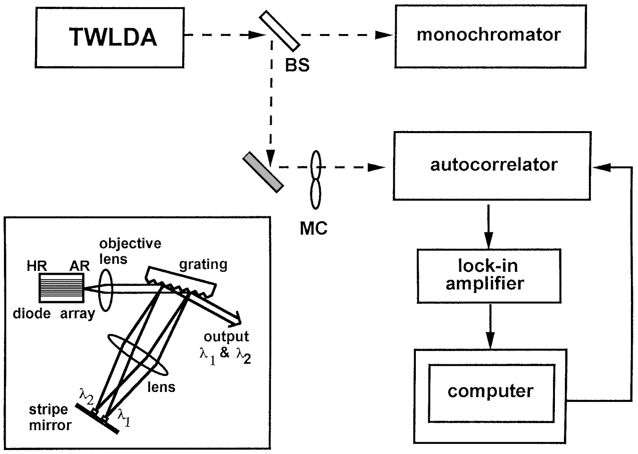

Fig. 1. Experimental setup. BS, beam splitter; MC, mechanical chopper. The inset shows the configuration of the TWLDA (HR, highly reflecting; AR, antireflecting).

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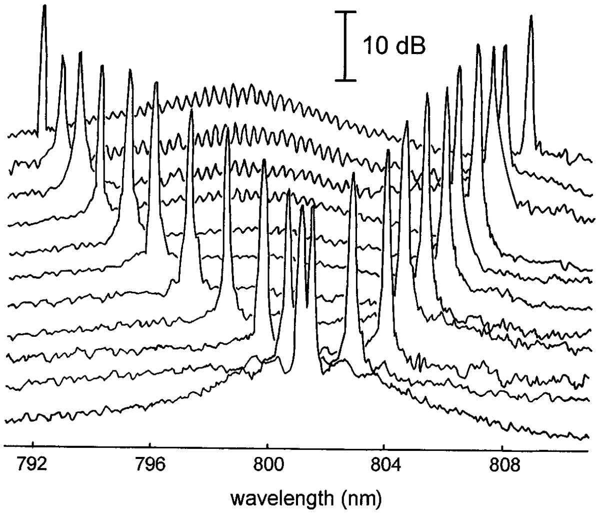

Fig. 2. Spectral separation of the two-color output of the TWLDA biased at 300 mA can be tuned from 0.32 to 17 nm.

is the largest tuning range of $\Delta\lambda$ of any cw two-color laser source reported to date.

The side-mode suppression ratios of the laser modes are more than 15–20 dB over the entire tuning range of $\Delta\lambda$. The minimum and maximum spectral separations are determined by the mode spacing (because of the finite reflectively of the antireflection-coated facet) and the gain bandwidth of the laser, respectively. The output power of each wavelength at maximum and minimum spectral separation was 10 and 1 mW, respectively, when the diode was biased at 300 ± 1 mA and $20 \pm 0.1\,^{\circ}$C. The threshold current of the laser was 260 mA. One can also generate dual-wavelength output by replacing the array with a single-strip laser diode.[12] The competition between the two modes is, however, quite strong. It is difficult to maintain simultaneous two-wavelength laser output. We attribute the stable two-color output from TWLDA to the pronounced spatial hole-burning effect in the gain-guided laser diode array.

The coaxial two-wavelength output of the laser is an intensity-modulated optical beam. The modulation frequency is just the beat frequency, $\nu_b = |\nu_1 - \nu_2|$, of the two resonant frequencies of the laser, ν_1 and ν_2. The intensity-modulated output of the laser can be expressed as

$$I(t) = (I_1 + I_2) + 2\sqrt{I_1 I_2}\cos(2\pi\nu_b t)\,. \qquad (1)$$

By tuning the spectral separation of the output of the dual-wavelength laser, this beat frequency can be quasi-continuously tuned from 0.15 to more than 7 THz. Because sensitive detectors with bandwidths exceeding terahertz are not available, we have used a noncollinear intensity autocorrelator to characterize the terahertz intensity-modulated signal. The time-averaged background-free correlation function of $I(t)$ is given by

$$G^{(2)}(\tau) = (I_1 + I_2)^2 + 2I_1 I_2 \cos(2\pi\nu_b\tau)\,, \qquad (2)$$

where τ is the time delay between the two arms of the correlator. Thus, in the ideal case, $G^{(2)}(\tau)$ is a sinusoid of period $1/\nu_b$. For the multiterahertz beat note this period corresponds to a spatial delay of the order of 100 μm, which can be easily measured. Information such as beat frequency, modulation depth, and linewidth of the modulated signal can be extracted from the correlation trace. Furthermore, it is possible to verify the presence of phase-coherent intermodulation sidebands by taking the Fourier transform of the autocorrelation fringes.

Figure 3 shows the output of the correlator as a function of the delay time. The circles are experimental data points. The solid curve is nearly a sinusoidal waveform (see discussions below) at 3.36 THz, corresponding to the beat frequency ν_b for two wavelengths, 797.27 and 804.39 nm. The contrast ratio of the correlation trace remains almost the same over a delay range of more than 10 modulation periods. This is an indication of the phase coherence or frequency locking between the two modes. We have also determined by using a Fabry–Perot interferometer that the laser linewidth for each wavelength is less than 100 MHz (instrument limited). Although the TWLDA was not actively frequency stabilized, the fluctuation in the resonant mode frequency was less than a few tens of megahertz, as estimated from the oscillogram from the scanning Fabry–Perot. We thus estimated that the linewidth of the beat signal was less than 200 MHz.

In our experiments I_1 and I_2 are equal. If ν_1 and ν_2 are phase locked, the contrast ratio of $G^{(2)}(\tau)$ or $[G^{(2)}_{\max}(\tau)/G^{(2)}_{\min}(\tau)] = 3$. Clearly the contrast ratio of the correlation trace in Fig. 3 is less than 3. This is due primarily to two effects. First, the far-field patterns of the laser output at the two wavelengths are different.[11] As a result, the two modes did not completely overlap spatially at the nonlinear crystal. This increased the background level of $G^{(2)}(\tau)$. Second, the spot size of the intersecting beams at the nonlinear crystal was found to be ≈ 250 μm. In comparison with other lasers this is rather large because of the divergence properties of the laser diode array. The self-delay effect of the noncollinear autocorrelator must then be considered.[13] Briefly, the modulated second-harmonic signals originating from different regions of the intersecting area of the two noncollinearly incident beams have experienced a different delay in

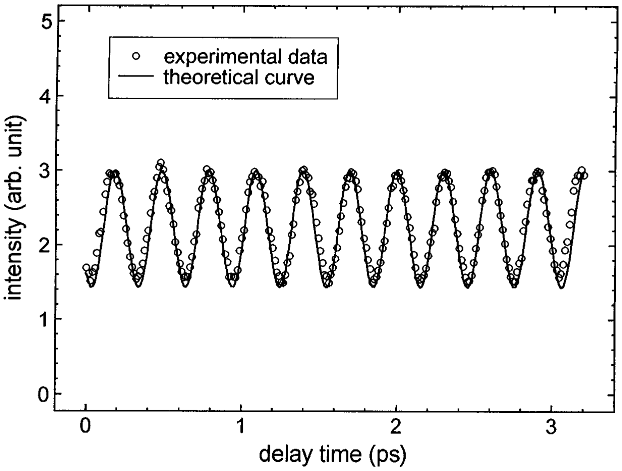

Fig. 3. Intensity autocorrelation trace for an optical carrier modulated at 3.36 THz.

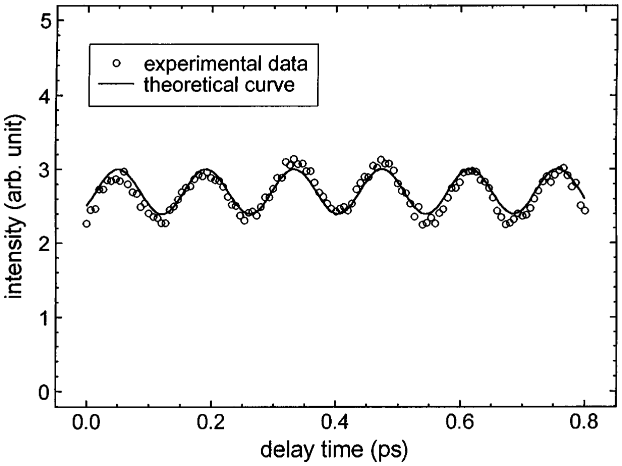

Fig. 4. Intensity autocorrelation trace for an optical carrier modulated at 7 THz.

the correlator. The time resolution of the correlator that is due to this effect is

$$\tau_r = \frac{nW \sin \phi/2}{c}, \tag{3}$$

where n is the index of refraction of the doubling crystal, c is the velocity of light in vacuum, W is the beam waist in the horizontal plane of the crystal, and ϕ is the angle at the nonlinear crystal made by the two incident beams. For our experimental configuration ($W = 250\ \mu\text{m}$, $\phi = 7.6°$), $\tau_r = 55.56$ fs. If we assume the self-delay to be a Gaussian distribution of τ with FWHM $= \tau_r$, the output of the correlator as detected by the photomultiplier will be the convolution of $\exp[-(\tau/\tau_r)^2]$ with $G^{(2)}(\tau)$, $G_r^{(2)}(\tau_1)$. It can be readily shown that

$$G_r^{(2)}(\tau_1) = (I_1 + I_2)^2 + 2I_1I_2 \exp[-(\pi\nu_b\tau_r)^2]\cos(2\pi\nu_b\tau_1). \tag{4}$$

The contrast ratio would be less than 3 and is given by $\{2 + \exp[-(\pi\nu_b\tau_r)^2]\}/\{2 - \exp[-(\pi\nu_b\tau_r)^2]\}$ if I_1 equals I_2. The solid curve in Fig. 3 is calculated by Eq. (4). It agrees quite well with the experimental data.

We have also performed the Fourier transform of the correlation trace. The linewidth of the terahertz beat signal determined from this analysis approaches the resolution limit (≈0.1 THz) of the present correlator, which is the inverse of the total delay time. The phase-coherent intermodulation sidebands have not been observed. This indicates that four-wave mixing in the gain region of the TWLDA does not approach the detection level under our experimental conditions.

Experimental results for 7 THz are shown in Fig. 4. This is the beat note of two modes spectrally separated by 14.89 nm. The contrast ratio is even smaller than that of 3.36 THz because the modulation period (145 fs) is very close to the time resolution that is due to the self-delay effect. Furthermore, the output power (≈1 mW) of the laser at the maximum spectral separation (for 7 THz) is approximately 10 dB lower than that for 3.36 THz. If the TWLDA is actively mode locked, a terahertz-rate modulation superimposed upon the sech^2 pulse envelope, similar to that reported in Ref. 4, is also observed.[14]

In summary, we have demonstrated generation of an intensity-modulated optical signal at a multiterahertz rate directly from a single laser diode source. With the diode array biased at only 1.15 times threshold, the modulation frequency or the beat frequency of the two modes of the TWLDA can be tuned from 0.15 THz to more than 7 THz. The spectral width of the beat note is estimated to be less than 200 MHz, or as small as 3×10^{-5} of the beat frequency (instrument limited). Still higher beat frequency and broader tuning range can be realized by biasing the laser at higher current. The multiterahertz beat signal was characterized by a noncollinear intensity autocorrelator. Experimental results are in good agreement with theoretical predictions.

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