Tunable cw THz Source with High-Precision Frequency Control

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***Abstract*—We realized a tunable continuous-wave terahertz (cw THz) source with MHz frequency resolution. The system is based on optical heterodyning of two near-infrared Distributed Feedback (DFB) diode lasers, each laser being stabilized by electronic feedback from a low-finesse quadrature interferometer. The control loop permits precisely linear laser frequency scans over >1200 GHz, and a beat signal linewidth of 1 MHz @ 80 ms time scale. Using GaAs photomixers and log-periodic antennae, we achieve an SNR of the THz power of > 70 dB at 100 GHz and 100 ms integration time, and still ~ 30 dB @ 1 THz. As an example for high-resolution THz spectroscopy, we characterize the transmission properties of a sub-wavelength metal grating.**

I. Introduction And Background

TERAHERTZ radiation bears great potential in imaging and spectroscopy [1]. One established method of generating tunable cw THz light is optical heterodyning [2]: a metal-semiconductor-metal structure ("photomixer") is irradiated with two near-infrared lasers of adjacent wavelengths, and a resonant antenna emits an electromagnetic wave at the THz difference frequency. Benefits of this technique are a wide bandwidth, low initial and operating costs, and simple implementation.

We developed a tunable cw THz source, which combines distributed feedback (DFB) diode technology and precise interferometric frequency control. This allows us to stabilize the laser frequency to arbitrary values within the diode's tuning range, achieving a frequency resolution on the 1 MHz level, yet maintaining a tuning range of > 1 THz.

II. Experimental Setup

Our THz source employs two DFB lasers (Toptica DL DFB) with center wavelengths of 855 nm, and 130 mW output power. The diodes were screened for large continuous tuning ranges (> 1000 GHz over a 40-45 K temperature sweep). Both laser beams are coupled into a fiber array made of single-mode, polarization-maintaining Panda fiber. From each input, approx. 1% of the light intensity is tapped off for frequency and power control. The main beams are mixed in a 2x2 fiber combiner, and the two outputs carrying the beat signal are connected to the THz transmitter and receiver, respectively (Fig. 1). Compared to a free-space design, the all-fiber setup improves the flexibility and power stability of the system.

For frequency stabilization, we use two low-finesse, temperature-stabilized etalons [3]. Each etalon generates a pair of interference signals with a relative phase of $\pi/2$. These

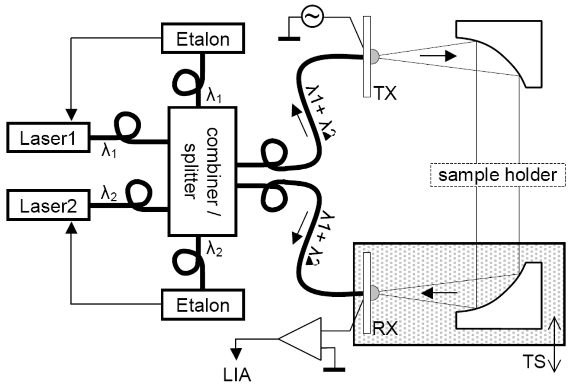

Fig. 1: Experimental setup. TX = transmitter, RX = receiver, TS = translation stage, LIA = lock-in amplifier.

signals are combined into a quadrature signal, the phase of which is a linear function of the optical frequency. This interferometrically measured phase is actively controlled by a PID regulator, which acts on both temperature and current of the DFB laser. The laser frequency remains actively controlled even during a scan, enabling precisely linear ramps of the THz difference frequency. The resolution of the frequency control loop is approx. 1/10 000 of the etalon free spectral range, i.e. on the 1 MHz level. An additional power control loop serves to maintain a constant average output power over the entire tuning range of the DFB laser.

The THz transmitter and receiver comprise low temperature grown (LTG) GaAs finger-photomixers, integrated within log-periodic antennae. The emitted THz beam is collimated by a parabolic mirror and focused onto the receiver by a second, identical mirror. We employ coherent signal detection, with the THz beam and the two-color laser beam superimposed on the receiver.

III. Results

Using interferometric frequency control, precisely linear frequency scans over 1200 GHz were realized. The power servo loop reduced the laser intensity variation to ± 7% over the entire scan range. A beat signal linewidth of 1 MHz at time scales as long as 80 ms was measured (Fig. 2). This is a noticeable difference compared to the unregulated lasers, where the beat FWHM amounts to > 3 MHz at 80 ms integration time. The long-term stability of the system was better than 20 MHz @ 24 hrs.

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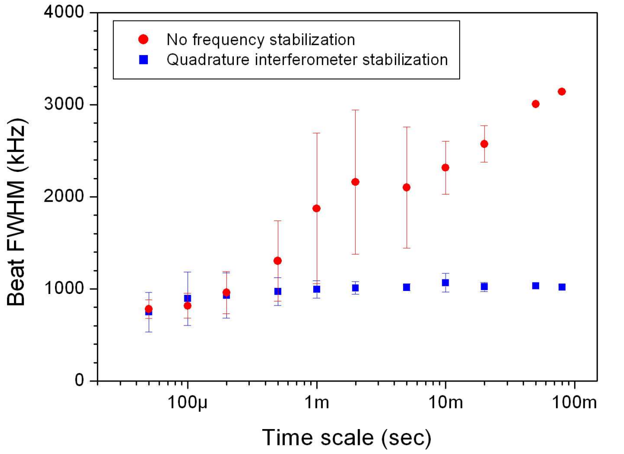

Fig. 2: Beat signal linewidth of two DFB lasers with and without frequency stabilization. The measurement was performed by dividing a data string of 80 ms into subintervals of different lengths (50 µs – 80 ms). Symbols and error bars denote the mean and standard deviation of the results obtained for the subintervals. Data points at 50 and 80 ms have no error bars as they represent only a single measurement.

In order to determine the signal-to-noise (SNR) characteristics of the THz signal, the difference frequency was varied from 100 .. 1100 GHz in steps of 10 GHz. For each frequency step, the phase between the THz signal and the optical beat at the receiver was equalized via a mechanical translation stage, and the receiver photocurrent was measured. The lock-in time constant was set to 100 ms. The noise level was determined by blocking the THz beam at the receiver, with otherwise identical settings. The average noise floor was 29 ± 3 pA.

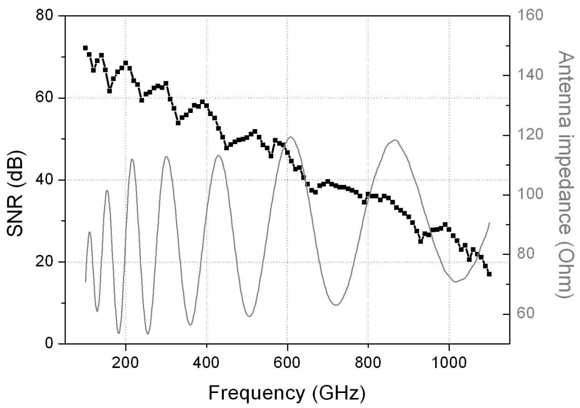

Fig. 3: Signal-to-noise performance. The SNR is computed by 20 log (I_p/I_{noise}), where I_p denotes the receiver photocurrent and I_{noise} is the noise floor, measured with blocked beam. The simulated antenna impedance is shown for comparison.

SNR levels of the THz power above 70 dB were attained at frequencies around 100 GHz (Fig. 3). This corresponds to an absolute amplitude of the photo current of > 110 nA and a THz power of ca. 200 nW. The reduced SNR towards higher frequencies mirrors the decrease of the photomixer efficiency. The "dips" seen e.g. at 120 GHz, 160 GHz, 240 GHz and 330 GHz are a result of the log-periodic design of the antenna. These minima correspond to the minima of the antenna impedance, a simulation of which is also shown in Fig. 3. The slight blue-shift of the simulation with respect to the measurement is attibuted to the fact, that the permittivity of bulk GaAs (ε = 12.9) was assumed for the simulation, rather than the effective permittivity of the LTG-GaAs layer on bulk GaAs, which is not precisely known. The SNR curve further shows the prominent water vapor absorption line at 560 GHz.

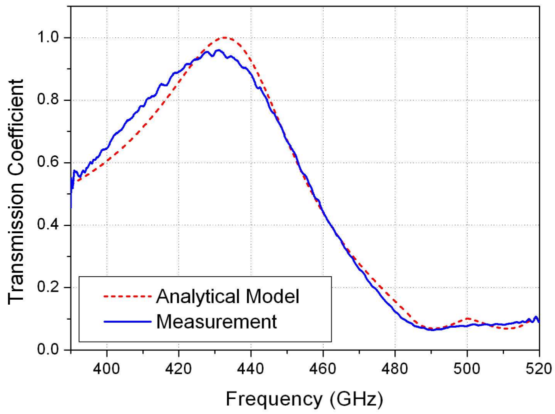

Fig. 4: Transmission measurement of a subwavelength grating, after normalization to the free-space reference. Excellent agreement is found with an analytical model.

As an example for high-resolution THz spectroscopy, a transmission spectrum of a subwavelength grating was recorded. Metal films with subwavelength perforations exhibit remarkable transmission properties, including narrow, highly resonant transmission peaks as well as points of zero transmission [4]. In our feasibility experiment, a grating made of Tombac was employed, with 70 periods of 600 µm each, a slit-width of 100 µm, and 200 µm thickness. The spectrum was normalized to the free-space reference and gated in time domain in order to eliminate reflections. The result, shown in Fig. 4, shows the expected resonance at 430 GHz, followed by a steep decrease in transmission. The obtained spectrum is in excellent agreement with the theoretical prediction. Sub-wavelength gratings can thus be used as THz bandpass filters.

In conclusion, we have realized an all-fiber-based cw THz system, which, to our knowledge, achieves the highest reported frequency resolution of tunable THz systems based on optical heterodyning. Further, the linear 1200 GHz scan of the frequency-controlled DFB laser likely represents the largest frequency scan of a diode laser with MHz precision.

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