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Fourier-transform photocurrent spectroscopy using a supercontinuum light source

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We demonstrate an implementation of frequency-encoded photocurrent spectroscopy using a super-continuum light source. The spectrally broad light is spatially dispersed and modulated with a special mechanical chopper design that permits a continuous wavelength-dependent modulation. After recombination, the light beam contains a frequency encoded spectrum which enables us to map the spectral response of a given sample in 60 ms and with a lateral resolution of 10 \( \mu \)m.

The spectroscopic properties of a medium are often measured directly by monitoring the absorption or scattering of light with a photo-detector. Such a direct measurement is not possible when the light causes thermal, acoustic, or electronic excitations, respectively, in photothermal, photoacoustic,1 or photoconduction spectroscopy.2

In the case of photo conductors, including solar cells, the spectral response is an important performance parameter. Its characterization requires that the wavelength of the source is scanned whilst the photocurrent is monitored. Typically, this kind of measurement is slow and, when using a lamp the spatial resolution is low. However, a high spatial resolution and high spectral brightness are necessary to characterize small structures at high power levels, as is of interest for the in-line characterization of concentrator solar cells3 or photo-conductive switches.

Here, we present a means to record the spectral dependence of photoconductors that makes use of a custom optical chopper. Our approach relies on a modulation scheme that simultaneously modulates the various frequency components of a dispersed spectrally broad source. This allows a Fourier decomposition of the signal. We have implemented the method with a super-continuum light source and are, therefore, able to characterize small structures with high spectral brightness. We study the influence of the substrate material on the excitation of photo currents in low temperature grown gallium arsenide (LT-GaAs) structures for wavelengths between 710 nm and 1.7 \( \mu \)m.

Fig. 1 schematically depicts the principle of our measurement scheme. A spectrally broad light-beam is dispersed by a prism (P1) and the spectral components are subsequently parallelized by a second prism (P2). The light then passes the key-component in our setup, the continuous frequency encoder (FE). This rotating disc is designed to exhibit a linear dependence between radial position and modulation frequency. In contrast to other spatial light modulators, our design does not depend on the number of modulation channels, and our encoder transmits the entire spectrum without any gaps. Different spectral components are modulated at different frequencies by the chopper disk.

The chopper wheel of Fig. 1 is designed such that the modulation frequency is a linear function of the radial distance from the center, \( f(r) = \frac{r}{R} \), and such that the maximum frequency, \( f_{\text{max}} \), is not more than \( 2 \times f_{\text{min}} \), where \( f_{\text{min}} \) is the smallest modulation frequency. In the schematic of Fig. 1, this corresponds to a faster modulation of the blue light. The functional dependence of the chopper wheel’s transmission \( T \) is given by

\[
T(r, \phi) = \Theta \left( \sin \left( f_{\text{max}} \frac{f(r)}{R} \left( \phi - \frac{\pi}{2} \right) \right) \right),
\]

where \( \phi \) is the angular position. The Heaviside step function \( \Theta \) transforms the sine function to describe solid chopper wheels that either block or transmit the light. In the Fourier spectrum of a signal generated during the time \( T \) of one full rotation at the rotation frequency \( f_0 \), the modulation-frequency

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resolution is given by $\Delta f = 1/T = f_0$. The number of resolvable channels $N = (f_{\text{max}} - f_{\text{min}})/f_0$. The difference between a continuous (here) and a standard discrete modulator with $N$ modulation channels is the possibility to improve the Fourier spectrum via zero-filling. This does not change the spectral resolution of the signal but enables one to localize sharp peaks or edges with a higher (sub-channel) resolution.

Fig. 2 shows a schematic of the measurement setup. We used a commercial pulsed super-continuum source with output between $\lambda = 450 \text{ nm}$ and $\lambda = 2.2 \mu m$ and pulse energies of $\approx 100 \text{ nJ}$ at a repetition rate of $41 \text{ MHz}$.

After passing the frequency encoder of Fig. 1, the light is reflected by a mirror (M1) and then travels back through both prisms, which re-collimate all spectral components of the beam. To ensure a channel separation of all channels, the beam is focused by the lens L1 before passing through the modulator wheel. After back-reflection, the frequency-encoded light hits a pickup mirror (M2), which directs the beam through a filter section and the focusing lens L2 onto the sample. The induced photocurrent is amplified using a transimpedance amp (FEMTO DLPCA-200). Afterwards, the voltage is sampled at 160 kS/s by a data acquisition device (NI USB-6212). Due to the continuous modulation of the optical wheel, there is an unavoidable discontinuity after one full rotation of the encoder wheel. The signal is, therefore, sliced into segments, each corresponding to a full rotation. These are synchronized to a reference signal. The signal is then convoluted with a suitable window function to suppress oscillations and subsequently zero-filled to improve the resolution. The wavelength scale is obtained via simulation of the dispersive elements or, as we have done it here, via a calibration measurement.

Photo-conducting switches built from LT-GaAs are widely used for THz generation with short-pulse lasers. Fig. 3 shows a typical photo-conductive switch for THz generation. To generate the $\sim$ps current transients, light pulses of $\sim 100 \text{ fs}$ are used to generate charge carriers, which are accelerated via an external electric field. Because of the band-gap of GaAs ($1.43 \text{ eV}$ at room temperature), only lasers with a center wavelength of less than $\sim 867 \text{ nm}$ can generate charge carriers directly out of the valence band. As fs-lasers at telecom wavelengths cost much less and allow for very simple and rugged all-fiber setups, there is a need for materials that are photo-conducting at longer wavelengths yet have a low dark-current. Materials like LT-InGaAs provide band-gap energies low enough for direct absorption but typically show a high dark-current, which limits the THz-performance. As described in Refs. 6 and 7, there are two-photon processes in LT-GaAs, which provide reasonable excitation rates and carrier lifetimes for THz generation at photon energies below the band-gap.

Our investigation of the THz performance of LT-GaAs based photo-conducting switches illuminated at $\lambda = 1.55 \mu m$ shows a marked difference between different substrate materials of the LT-GaAs layer. Due to the near TEM00 beam profile of the supercontinuum light source, we were able to record the photo-current spectra between $\lambda = 710 \text{ nm}$ and $\lambda = 1700 \text{ nm}$ with a spatial resolution of $\sim 10 \mu m$ at 16 Hz. The measurements shown in Figs. 4 and 5 were taken with a bias-voltage of 10 V and with 7 mW of optical power.

We investigated two different material combinations. Sample 1 is LT-GaAs on semi-insulating (SI)-GaAs, and sample 2 is a LT-GaAs layer van-der-Waals bonded to a SI-silicon substrate. Both samples show the same electrode configuration: two parallel metal-strips of 10 $\mu m$ width and 60 $\mu m$ distance, and a connecting strip with a 5 $\mu m$ gap.
(active area) for the THz-pulse generation. To facilitate characterization, both samples were used as detector antennas in a THz TDS-System, with sample 2 showing a much stronger dependence on the exact focal position and optical power. This gave rise to the hypothesis that significant contributions to the signal come from charge carriers generated in the substrate not the LT-GaAs layer.

The measurements of Fig. 4 are taken at points 1-2 and 1-3 (Fig. 3) for the GaAs- and Si-substrate, respectively, and are normalized to the gap-illuminated peak current. Both samples show very similar photo-current spectra for illumination at 1. When illuminated at point 2 (at larger distance to the metal conductors), the photo current is dominated by long-lived carriers in the substrate. The single-photon LT-GaAs peak is strongly suppressed for sample 1 and vanishes for sample 2. At $\lambda = 1.5 \mu m$, the photo current of sample 1 is about one order of magnitude higher than the photo current of sample 2, because the Si-substrate does not contribute very much to the current, as measured at point 3. As the two-photon absorption is a nonlinear process, the power density has to be maximized in the LT-GaAs layer of sample 2, what makes it more susceptible to misalignment than sample 1.

To demonstrate the superior spatial resolution of our method, we performed a linear scan across sample 2, indicated by the black arrow in Fig. 3. Figure 5 is a false color plot of the measured photocurrent which clearly shows the different material properties of the Si-substrate and the LT-GaAs layer. At distances larger than 15 $\mu m$ from the gap, the current is dominated by charge carriers generated in the Si-substrate at short wavelengths and at wavelengths above the band-gap by carriers generated in the LT-GaAs layer. In the gap-area, close to the metal conductors, the short-lived carriers generated in the LT-GaAs can contribute to the photocurrent and dominate the signal.

In conclusion, we demonstrate “one shot” frequency-encoded photo-current spectroscopy using a continuously structured frequency encoder and a supercontinuum source. The same encoding scheme could also be implemented in photo-thermal, photo-acoustic measurements, or in hyperspectral imaging. We present photo-conduction measurements of THz photo-conductive switches with a spatial resolution of 10 $\mu m$. The measurement speed together with the spectral brightness and bandwidth and the small spot-size make this approach suitable for high resolution photo-current mapping or in-line inspection of solar cells.

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