GIGAOPTICS
femtosecond technologies

Large-Area Photoconductive THz Emitter

TERA-SED

Operating manual

IT IS MANDATORY TO READ THIS MANUAL BEFORE ATTEMPTING TO USE THIS DEVICE. PERMANENT DAMAGE MAY OTHERWISE RESULT !

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1. General Description / Operating Principle

Tera-SED stands for **Tera**hertz - **S**calable **E**mitter **D**evice, a novel type of photoconductive large-area Terahertz (THz) emitter featuring an interdigitated MSM (metal-semiconductor-metal) electrode structure. The generation of THz radiation is based upon optical generation of charge-carriers inside a GaAs semiconductor substrate using femtosecond laser pulses and the subsequent acceleration of the photo-generated carriers by use of an applied bias field. The large active area provides the means to achieve high THz field strengths and to adjust the laser spot size in order to optimize the overall performance of the THz setup.

The Tera-SED is permanently mounted inside a special holder which allows safe and convenient installation into standard 1-inch optics mounts. The metal holder also permits to reliably connect the device to the bias voltage supply leads. It should at no time be attempted to remove the device from its holder. External cooling of the device is not required.

The operating principle of the Tera-SED is described in detail in Ref. [1]. The principle layout of the device is shown in Fig. 1. The interdigitated MSM electrode structure (shown in red and yellow in Fig. 1) is processed onto the GaAs substrate using photolithography. Applying a bias voltage induces an electric field between the electrodes with the direction of the electric field alternating between adjacent electrode pairs. In order to achieve a uni-directional electrical field across the whole device area, a second metallization layer (shown in green) covers every second electrode gap. This second metallization layer is electrically insulated from the first. It is mandatory to keep the applied bias voltage within the specified range (see operating instructions and data sheet) to prevent permanent damage to this insulation layer.

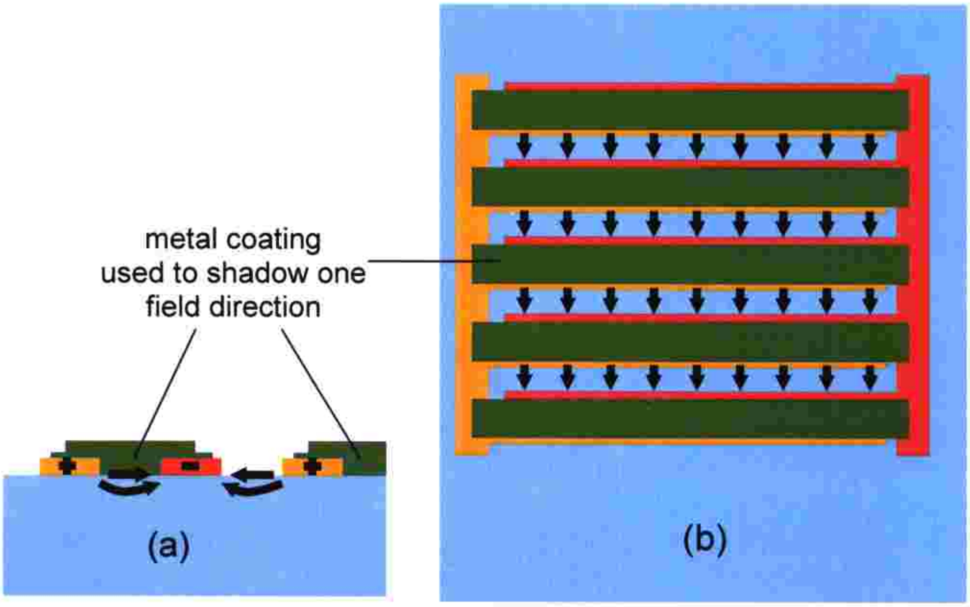

Fig. 1: Principle Tera-SED design: (a) cross-sectional view and (b) plane view.

Optical excitation is to be done at normal incidence on the metallized (front) side of the device. THz radiation is emitted from both sides of the device, however, the normal mode of operation is to collect the THz radiation emitted from the substrate (rear) side (see next section).

The active area of the Tera-SED is finally coated with SiO_2. The SiO_2 layer serves as a protective coating to prevent damage to the rather soft gold metallization layer. Refer to the operating instructions section for a description of proper cleaning procedures.

2. Basic setup for operating the Tera-SED / System requirements

Figure 2 shows a sketch of the optical setup which is used for testing the Tera-SED device. This sketch is intended to provide a general guideline of how to implement the device into a typical experimental setup.

In this test setup, a Ti:Sapphire fs-oscillator with a pulse repetition rate of 78MHz is used to deliver the optical excitation pulses to the device. The pulse duration is 50 fs. The optical beam is focussed onto the metallized side of the device with a spot size of 300 µm FWHM. The THz beam emitted from the rear side of the device is collected and guided by use of off-axis parabolic mirrors (effective focal length 101.6 mm and 50.8 mm for M1 and M2, respectively). The THz radiation is detected electro-optically using a 25 µm-thick, 110-oriented ZnTe crystal glued onto a glass plate. Details about the electro-optic detection of THz radiation can be found in Refs. [2,3]. In the test setup the optical beam used for the electro-optical detection is aligned collinearly with the THz beam by use of a tin-doped, Indium Oxide (ITO)-coated fused silica plate [1,4].

The bias voltage for the Tera-SED is applied in pulsed from, i.e., using voltage pulses derived from a signal/function generator. The optically generated THz pulse train is then best detected using a lock-in amplifier locked to the frequency of the pulsed bias voltage. Alternatively, the Tera-SED can be DC-biased while the optical excitation beam is modulated with a mechanical light-chopper. However, using voltage pulses with a repetition rate above 1 kHz will result in a better signal/noise ratio compared to the mechanical chopper approach.

The requirements of the laser system are as follows:

- **Central wavelength shorter than 860 nm**
  (to facilitate carrier generation in GaAs)

- **Ultrashort fs-laser pulses, i.e., shorter than 100 fs FWHM**
  The use of pulses with a duration of more than 100 fs is possible, however, this will lead to a reduced THz bandwidth

To prevent permanent damage to the device, certain maximum values of *laser power and fluence* are not to be exceeded at any time. Please refer to the provided data sheet in order to see which power and fluence can be safely used!

Typical requirements for the electrical power supply are as follows:

- **Voltage: up to 50 Volts**
- **Current: up to 100 mA**
- **DC or rectangular-shaped voltage pulses (up to 100MHz pulse repetition rate)**

To prevent permanent damage to the device, certain maximum values for the applied *voltages and resulting currents* are not to be exceeded at any time. Please refer to the provided data sheet in order to see which voltages and currents can be safely used!

Please follow the operating instructions to set a safe the bias voltage. For increased bias voltages, the duty cycle of the bias voltage has to be reduced to keep the dissipated heat in the device below the damage threshold! Please refer to the data sheet for specific values!

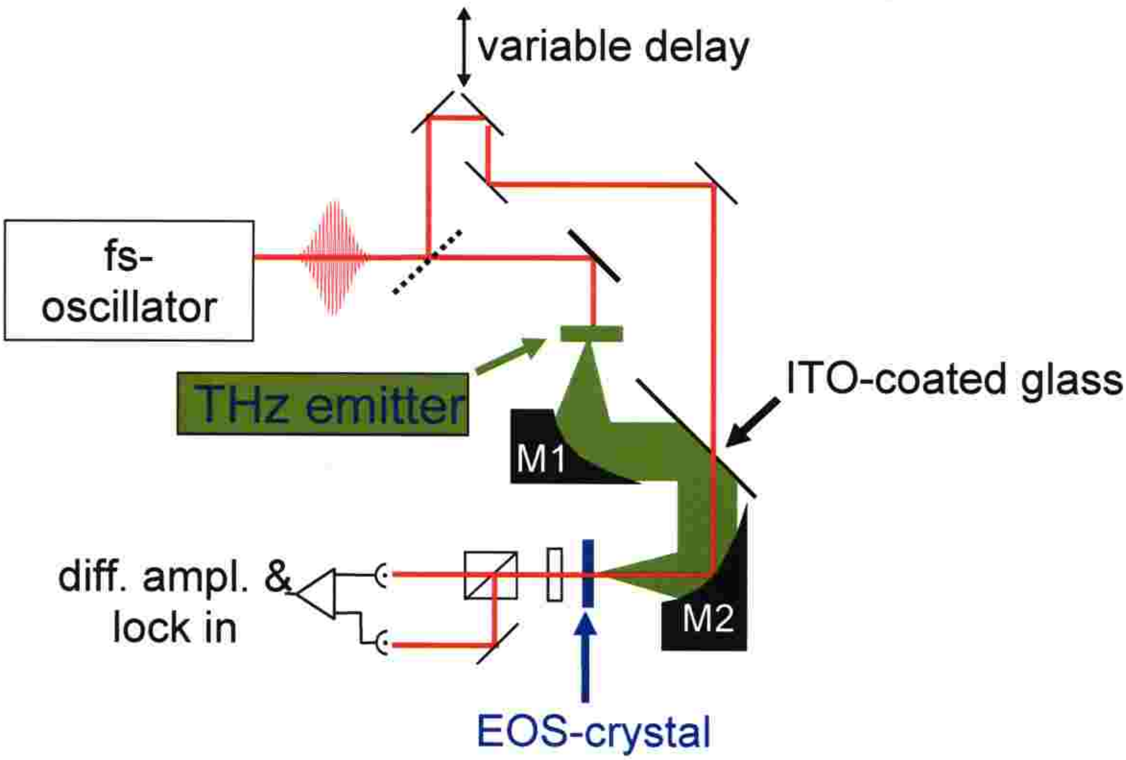

Fig. 2: Typical Tera-SED test setup.

3. THz emission characteristics from Tera-SED

3.1. THz waveforms, spectra and power

Figure 3 shows typical THz waveforms and power spectra for four different bias field strengths. Bias fields of 20 kV/cm, 40 kV/cm, 60 kV/cm and 100 kV/cm correspond to externally applied bias voltages of 10 V, 20 V, 30 V and 50 V, respectively. The modulation frequency of the rectangular bias voltage was 50 kHz in all cases. The duty cycle was 15 %. The laser power was 100 mW (pulse energy 1.3 nJ) focussed to a spot-size of 80 µm (FWHM) on the device.

As shown in Fig. 3a, the THz field amplitude achieved in this configuration exceeds 60 V/cm for the highest bias voltage. THz field amplitudes of more than 1 kV/cm using this device structure are reported [5]. The THz field amplitude was calculated from the relative intensity change of the probe beam on the balanced detectors as described by Planken et al. [6]. The power spectra (Fig. 3b) are normalized to the maximum. Higher carrier acceleration fields enhance higher frequency components. This effect is explained in detail in Ref. [1].

Figure 4 shows the dependence of the THz field on the excitation density. An excitation density of 3×10^{17} cm^{-3} corresponds to approximately 600 mW average laser power (pulse energy 7.7 nJ) using a spot-size of 300 µm (FWHM). In this range, the THz field increases linearly with excitation density. Hence, the THz power increases quadratically with laser power. For excitation densities in the 10^{18} cm^{-3} range, a sublinear increase of the THz field with increasing excitation density is observed. This effect is due to ultrafast screening of the acceleration field by the photogenerated carriers [1].

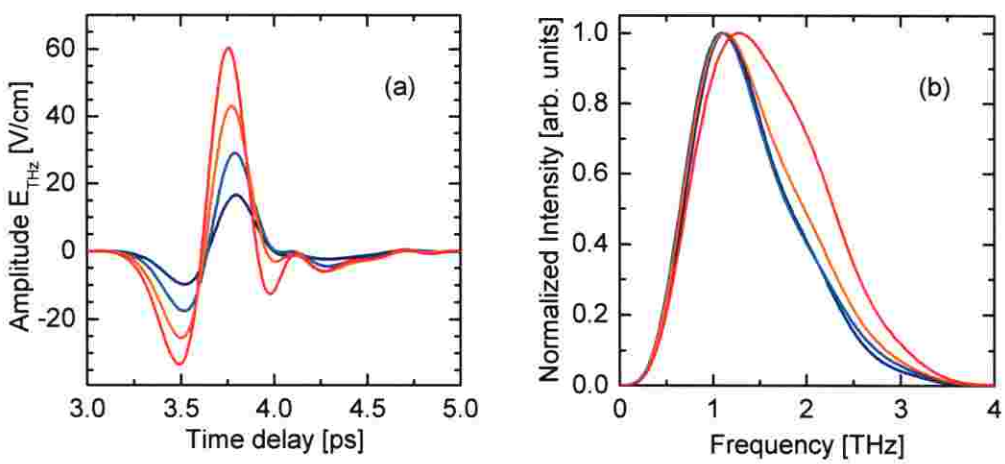

Fig. 3: THz waveforms (a) and normalized power spectra (b) for different electric bias field strengths (blue: 20 kV/cm, cyan: 40 kV/cm, orange: 60 kV/cm, red: 100 kV/cm).

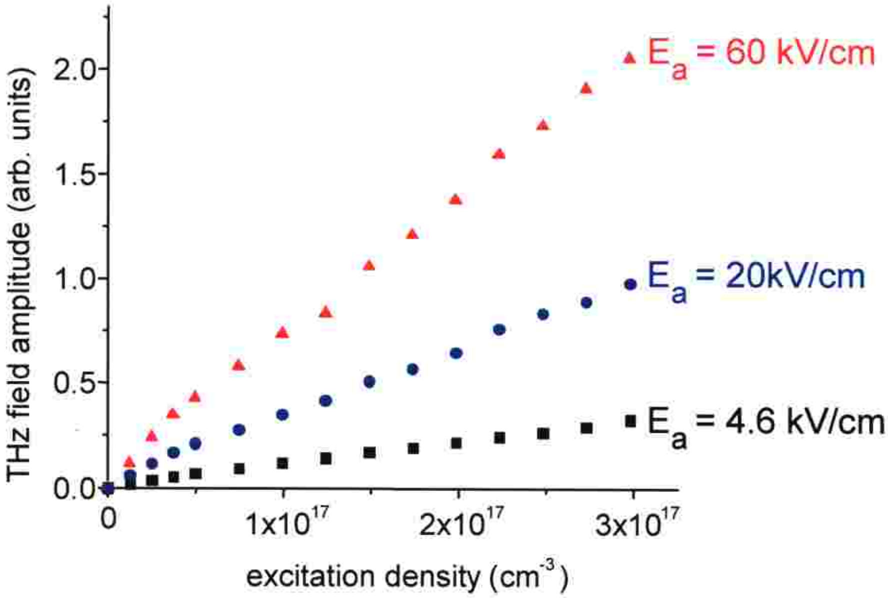

Fig. 4: Excitation density dependence of the generated THz field.

To further characterize the device's properties, the size of the THz spot on the ZnTe sensor crystal was mapped out. The result is shown in Fig. 5. An almost Gaussian profile with a FWHM of about 1 mm is found. The beam profile is slightly elliptical owing to a certain degree of ellipticity of the optical excitation spot. With the knowledge about the THz profile and the THz waveform reported in [5], a THz power of 0.5 mW for an acceleration field of 60 kV/cm is obtained. This is the power emitted while voltage is applied. Thus, in this case, the average power is 50 µW due to the duty cycle of 10%. The conversion efficiency of laser power to THz power is 0.8×10^{-3}.

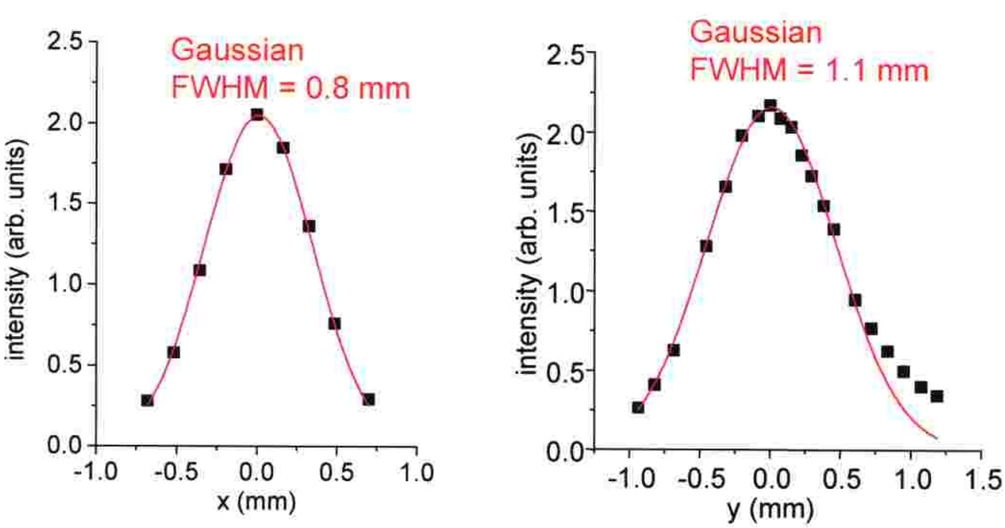

Fig. 5: THz beam profile on the electro-optical sensor crystal in the horizontal (left panel) and vertical (right panel) direction.

3.2. THz beam properties

As outlined in the preceding section, the THz beam could be focussed to a spot-size of 1 mm (FWHM) with the test setup. By placing apertures at different positions in the setup, it was found that the opening angle of the THz beam (300 µm spot-size of the exciting laser beam) is of the order of 20°. This opening angle determines the free aperture required for the setup described on page 4 and 5 in order not to disturb the terahertz beam. The opening angle for longer wavelength components can be larger (~30°) and for shorter wavelength components smaller (~15°). In all cases, the opening angle strongly depends on the optical excitation geometry.

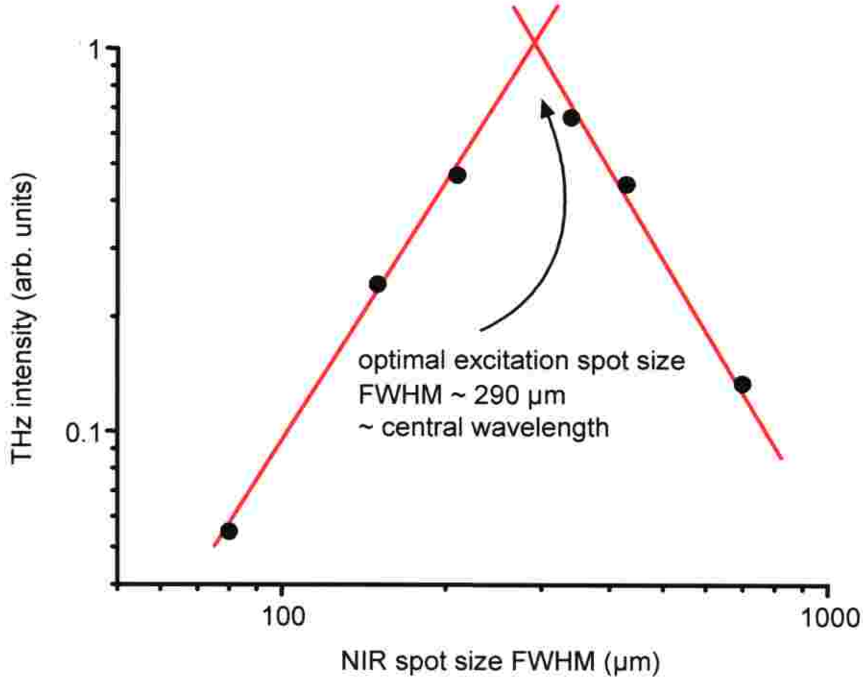

Fig. 6: Dependence of the THz intensity on the laser spot size.

Figure 6 shows the dependence of the emitted THz intensity on the spot-size of the excitation beam for constant power. The graph indicates that, for a given laser power, an optimum spot-size exists. This optimum spot-size is of the order of the central wavelength of the THz beam. If the spot size is much smaller than the THz wavelength, from diffraction theory it follows that [7]:

$$P_{THz} \propto P_{NIR}^2 r^2 \quad .$$

With P_{THz} being the THz power, P_{NIR} the excitation laser power, and r the radius of the excitation spot. In the opposite limit, with the optical spot size much larger than the THz wavelength, THz field and laser power are connected via the following relationship:

$$\frac{P_{NIR}}{\pi r^2} = I_{NIR} \propto n \propto E_{THz} \,. \qquad (1)$$

Here, I_{NIR} is the laser intensity, E_{THz} is the THz field strength, and n is the excitation density. This is valid in a regime where screening does not limit the THz emission, i.e., for excitation densities up to about 2×10^{18} cm^{-3}.

Since for the THz intensity

$$I_{THz} \propto E_{THz}^2 \propto (P_{NIR} / \pi r^2)^2$$

and for the THz power

$$P_{THz} = I_{THz} \pi r^2 \,,$$

it follows that

$$P_{THz} \propto \frac{P_{NIR}^2}{r^2} \,. \qquad (2)$$

Similar dependencies have also been found for THz generation by optical rectification [8].

Even though the optimum laser spot-size is about 300µm - for a given laser power - it can be useful for certain types of experiments to operate with different spot-sizes. For example, imaging applications might require to produce a parallel THz beam with a diameter much larger than the wavelength. For this purpose, the Tera-SED should be excited with a parallel laser beam of large spot-size.

To this end, experiments using an amplified Ti:sapphire laser system with a repetition rate of 1 kHz were performed [5]. In this experiment the laser spot-size on the Tera-SED was 5 mm. Maximum THz field amplitudes of up to 6kV/cm are obtained for an excitation density of 1.7×10^{18} cm^{-3} (pulse energy 10µJ). Due to field screening saturation of the THz emission is expected for higher excitation densities. However, a reduction in THz emission was also observed in these experiments. This may be due to low-intensity pulses preceeding the main, amplified excitation pulse. These low-intensity pulses produce carriers which discharge the device and, thereby, decrease the acceleration field.

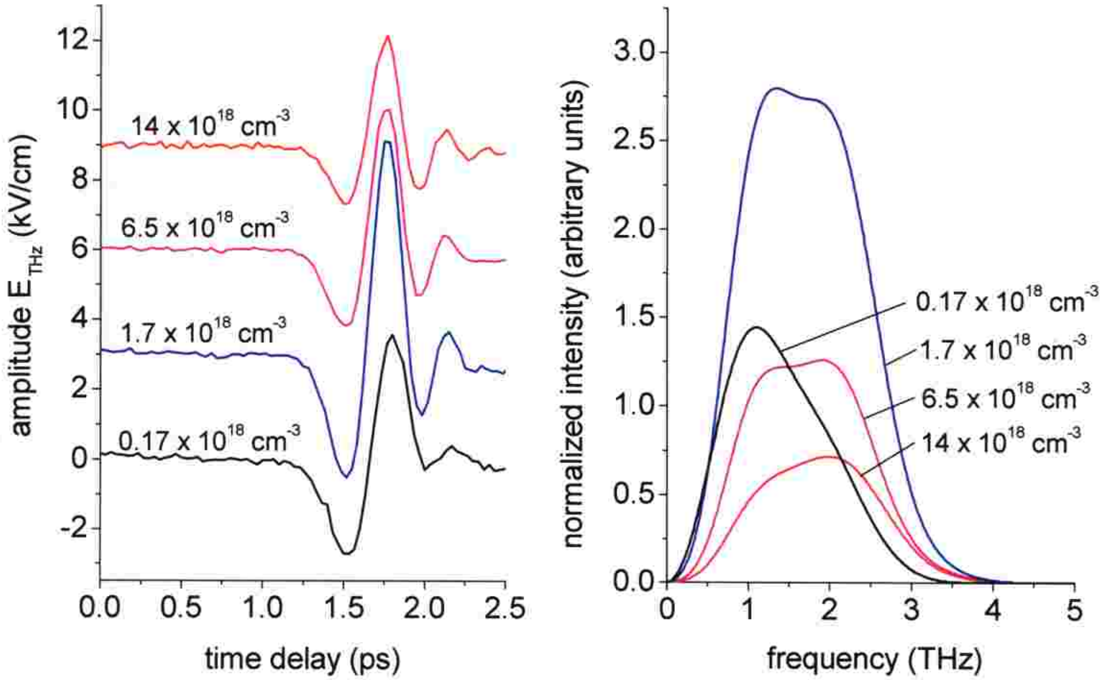

Fig. 7: Fig. 3: Terahertz waveforms (left panel) and normalized power spectra (right panel) for different optical excitation densities.

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[4] T. Bauer, J. S. Kolb, T. Löffler, E. Mohler, H. G. Roskos, and U. C. Pernisz, J. Appl. Phys. **92**, 2210 (2002).

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[6] P. C. M. Planken, H.-K. Nienhuys, H. J. Bakker and T. Wenckebach, J. Opt. Soc. Am. B **18**, 313 (2001).

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[8] J. Z. Xu and X.-C. Zhang, Opt. Lett. **27**, 1067 (2002).

4. Operating instructions for the Tera-SED

Please read and follow these instructions carefully in order to achieve the best performance of the device and to prevent permanent damage.

CAUTION - Failure to observe these instructions will constitute improper use of the device and the warranty on the device will be invalidated.

4.1 Inspection, mounting and cleaning

The Tera-SED is permanently mounted inside a special holder allowing safe and convenient installation into standard 1-inch optics mounts. This holder also allows to reliably connect the device to the bias voltage supply leads using the copper connector blocks on either side, see Fig. 8. After unpacking the Tera-SED, please inspect it and check for possible damage. To this end, check that

- the Tera-SED rests firmly in its holder
- the front and rear surface of the Tera-SED do not show cracks or severe scratches. Minor scratches on the metallized front surface are not a harmful flaw – in doubt, please contact Gigaoptics for clarification.
- the electrodes of the Tera-SED are soldered to thin wires which in turn are connected to the copper connector blocks. In case your device is a Tera-SED 3/2, please refer to the data sheet and/or page 16 of this manual concerning the electrical connections.
- the wires are stabilized

Insert the electrical leads from the voltage supply into the holes drilled into the copper connector blocks from the direction pointing away from the device (Fig. 8, arrows) and fasten securely using the clamping screws (Fig. 8, red circles). Polarity is not important at this point.

The copper wires connecting the device's electrodes to the copper connector blocks are very delicate – do not touch them! Always use great care when handling the device! Never attempt to remove the device from its metal holder!

Proper safety procedures must be observed at all times when connecting / disconnecting electrical leads to / from the device. Ensure that the voltage supply is switched-off. Take appropriate measures to avoid static discharge!

Only the metallized (front) side of the device is to be used for optical excitation! Excite at normal incidence and collect THz radiation emitted from rear side.

Should dust be present on any of the device's surfaces it can be carefully removed with a jet of dry air. Should the surface become contaminated more severely, it may carefully be cleaned with lens cleaning tissue and propanol.

Take special care not to damage the thin copper wires when cleaning the device! Do not use any other cleaning method than described here.

Fig. 8: Tera-SED mounted into 1-inch optics mount. Insert electrical leads from the voltage supply into the holes drilled into the copper conector blocks (orange arrows) and fasten securely with the metal clamping screws (red circles).

Note the metallization layer on the device's front side. This side is to be used for optical excitation only.

4.2 Test procedure for current-voltage characteristic

To ensure that the Tera-SED is functioning properly, the current-voltage characteristic should first be determined without laser irradiation. To this end, follow the procedure outlined below:

- make sure that the Tera-SED is not illuminated by any other direct light source
- connect the Tera-SED to a function generator that allows to apply voltage pulses with a duty cycle of 10 %. The duty cycle is given by the duration of a single voltage pulse devided by the period of the voltage pulse train.
- connect an Amperemeter (set to DC current) in series with the Tera-SED and the function generator. The amperemeter serves to measure the **average current** flowing through the device. The **actual current** during a voltage pulse will be this value devided by the duty cycle.
- connect an oscilloscope in parallel to the Tera-SED to monitor the voltage on the device.
- measure the current-voltage characteristic, i.e., monitor the current as function of increasing voltage, starting from the lowest voltage.
  Do not exceed the maximum bias voltage and do not exceed the maximum dissipated power specified in the data sheet!

In Fig. 1 of the provided data sheet the dark-current voltage characteristic of your individual Tera-SED is shown. This characteristic was measured with rectangular-shaped voltage pulses with a repetition rate of 10 kHz and a duty cycle of 10%. You should be able to reproduce this characteristic with a tolerance interval of 10 %.

Since the current may increase significantly at higher voltages, it is mandatory to not exceed the limits stated in the data sheet when testing or operating the Tera-SED! Please refer to the data sheet for the exact values specific to your device!

It is strongly recommended to also use the electrical setup described above when operating the Tera-SED with pulsed laser illumination:

- The Amperemeter allows to monitor the **average current** (dark current + photocurrent) flowing through the device. You will therefore be able to easily see if you are operating the Tera-SED below the damage threshold which is determined by Ohmic heating.

- The oscilloscope / Voltmeter allows to monitor the voltage applied to the device. The voltage on the Tera-SED may change as you change the laser power incident on the device. This is due to a change in the device's resistance. The magnitude of this effect will depend on the output impedance of the employed voltage generator.

Before integrating the Tera-SED into your THz setup, ensure that the laser power delivered to the device is well below the damage threshold. **To this end, the laser power and the spot-size have to be determined in advance.**

The central wavelength of the laser has to be below 860 nm in order to facilitate carrier generation in GaAs.

Please refer to the data sheet for appropriate values of the laser power.

4.3 Performance limits / possible causes of device breakdown

Please note that severe damage to the Tera-SED can be caused by the following conditions:

1. **Dielectric breakdown**
   Extremely large electric field strengths may occur at the edges of the electrodes. These field strengths have to be kept below the threshold for dielectric breakdown. Therefore, voltages which are too high can damage the device, even at small currents. It is, therefore, mandatory to never exceed the maximum bias voltage specified on the data sheet.

2. **Damage caused by high laser intensity**
   The Tera-SED can be damaged if the laser intensity in the excitation spot is too high. Even though this type of damage is locally constrained it affects the insulation layer and, thereby, leads to overall destruction of the device. It is mandatory to pre-determine and control both laser power and excitation spot-size to ensure that both parameters are within the specified range.

3. **Damage caused by Ohmic heating**
   Both dark current and photocurrent contribute to ohmic heating of the Tera-SED. To ensure that the device does not heat up to temperatures which can damage the metallization layer, the value obatined from the product of average current, applied bias voltage and duty cycle has to be kept below the specified value, as stated on the data sheet.

   The data sheet specifications are given for modulation frequencies above 10 kHz. Note that for lower modulation frequencies - as the pulse duration becomes longer - the heat produced during a pulse may exceed the damage threshold. Therefore, for lower voltage pulse repetition rates, either the bias voltage, the duty cycle, or the laser power (determining the photocurrent) has to be reduced.

4.4 Operating environment

The Tera-SED is only to be operated in a standard optical laboratory environment, i.e., at room temperature, non-condensing humidity, and in dust- and oil-free air.

In order to avoid absorption of THz radiation by water vapor it is recommen-ded to purge the THz setup with dry air or gaseous nitrogen.

4.5 Special instructions for Tera-SED3/2 devices

The Tera-SED 3/2 consists of two individual THz emitters with an active area of 3mm x 3mm each. One electrode of each emitter is connected to the same copper connector block. The second electrode of **one** emitter is initially connected to the other copper connector block.

Hence, by connecting the electrical leads from the voltage supply, this certain "first" emitter element will be biased and can be used for the generation of THz radiation when illuminated with optical laser pulses.

The remaining "second" emitter is also equipped with thin connector wires and may also be connected to **both** connector blocks, at the same time with the first emitter. However, this is not recommended, since this connection could lead to the destruction of both elements if the first element is damaged.

Therefore, it is recommended to initially use the first element only, which is already connected upon delivery. In case the second element is to be used (e.g. if the first element was damaged), disconnect the wire from the connector block and connect the other remaining element.

The wire may also be soldered to the connector block. Soldering can be easier if the copper block is heated using a hot plate or a hot air gun. Heat to a temperature of about 80°C. Please note: at higher temperatures the nylon screws may melt. As an alternative to soldering, conducting silver paint or conducting epoxy may be used to glue the wire to the connector block. Note that silver paint will not have the same mechanical stability as conducting epoxy or a soldered connection.

If, in the course of reconnecting emitter elements, the connection between the thin wire and the element should fail, you may try to carefully solder or glue the wire to the electrode yourself. If in doubt or unsure about the correct procedure, please contact Gigaoptics for assistance.

5. Liability

Gigaoptics GmbH accepts no liability for damage to persons or property caused by incorrect or unsafe use of any of its products, this is the sole responsibility of the user. Proper safety regulations for the use of these products must be observed at all times.

6. Warranty

Gigaoptics GmbH warranties its products for 12 months (unless otherwise stated) from date of shipment. This warranty is subject to the product not being mistreated. Mistreatment involves any of the following:

- Any deviation from the operating instructions provided within this manual. Among these especially:

- Attempting to remove the device from its metal holder
- Cleaning the device in any other fashion than described in this manual
- Operation in hostile or unclean environment as outlined in the operating instructions
- Any damage caused by static discharge
- Any damage due to exceeding the specified laser power and fluence values
- Any damage due to exceeding the specified voltage and current ratings

The definition of mistreatment in its applicability to the warranty is at the reasonable discretion of Gigaoptics GmbH.

Gigaoptics' obligation under this warranty is limited to the replacement or repair of the device which, having been returned to the factory, is found to be defective, and that the defect was not caused by factors external to the device. Any replacement part/product is under warranty for the remainder of the initial product warranty period.

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