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Spatial characterization of light detectors with nanometric resolution

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Abstract

The miniaturization of light detectors in the visible and infrared has produced devices with micrometric and sub-micrometric spatial features. Some of these spatial features are closely linked with the physical mechanism of detection. An example of these devices is an optical antennas. To spatially characterize optical antennas it is necessary to scan a probe beam on the plane of the optical antenna. The mapping of this response is then treated and analyzed. When the response of the antenna is monitorized at visible or near-infrared frequencies, a sub-micron scanning step is necessary. In this paper we show the experimental set-up of a measurement station having a spatial resolution of 50 nanometers. This station is devoted to spatially characterize micrometric detectors, and specially optical antennas. The origin of the uncertainties of the measurement protocol is shown and practically analyzed. This station is also applied for characterizing the temporal, spectral, and polarization sensitivity specifications of light detectors with the previously mentioned resolution.

1.- Introduction

The development of new types of optical detectors in the infrared and visible ranges has compelled the efforts to improve the techniques for characterizing and measuring their properties. Among the new kind of detectors currently developed are optical antennas. The lateral dimensions of an optical antenna are below the detection wavelength and the expected responsivity map is confined very closely to the material structure of the antenna. Besides, optical antennas are sensitive to the polarization state of the inciding light. Some other measurements of the time response characteristics need to evaluated by registering the response of the detector to light stimulus with increased temporal frequencies.

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In this contribution we present the design of a measurement station with nanometric resolution specifically designed for optical antennas characterization. Besides this primary detection objective, it can be applied to the characterization of some other detectors, or arrays of detectors in the visible and the near infrared. A detailed explanation of the elements involved in the measurement station is given in Section 2. Besides the data gathering, the analysis of the data needs some measurement and analytical tools that need to be address to make the experimental set-up fully operative and useful. Among these auxiliary packages we have previously developed and demonstrated the application of recursive deconvolution methods. This strategy allows a detailed characterization of the spatial responsivity of the detectors. These procedures are described in Section 3. In Section 4 we have analyzed briefly the sources of uncertainties of the obtained data. The effect of the spatial noise on the results of the spatial response characterization also analyzed in more detail. Finally, section 5 summarizes the main conclusion and results of this contribution.

2.- Experimental Set-Up Capabilities

The characterization of the spatial response of light detectors is somehow a residual task for most of the applications. However, when using new types of detectors or when they are arranged or shaped as customized designs, the knowledge of the spatial response is crucial to understand and validate the tested devices. Typically, light detectors are much larger than the detection wavelength. The area of the individual units of dense packed array detectors is typically above 100 λ^2. This order of magnitude is preserved, or even surpassed, in the infrared. In these cases, it is possible to create a probe light beam having an area of about 10 λ^2. The beam is scanned onto the light detector and the response is analyzed and properly processed. The final result is the spatial response of the detector. The optomechanical elements are properly configured to meet the required specifications in travel range, accuracy and repeatability.

In the recent past and nowadays there exists an intense effort in the development of miniaturized light detectors with improved performance and capabilities. Among these new concepts arising the infrared detection panorama are the optical antennas, or antenna-coupled detectors. As it can be demonstrated in the literature, they are capable of detecting light from the visible to the millimetric wavelength range [1,2]. Intrinsically they are sensitive to the state of polarization of light, and can be customized to fit specific needs in the detection of light. Moreover, they work at room temperature without need of any cryogenic or cooling subsystems. Another very interesting feature of optical antennas is related with their tiny dimensions. Antennas are known as electromagnetic radiation detectors scaled to the wavelength of the detected radiation [3,4]. The size of an optical antenna is therefore associated with the wavelength of the light. Even more, typical designs, as dipole antennas, are dimensioned in the sub-wavelength range. The actual dimensions of these devices shrink with the detected wavelength. A few years ago we demonstrate that optical antennas resonate at optical frequencies, opening the way for a new kind of detection mechanism in the visible range. Then, the characterization of these devices is basic to properly understand the applicability of new designs and the behaviour of the fabricated devices. The measurement of the spatial response is an important part of this analysis and should be addressed using high-resolution and high-performance measurement stations.

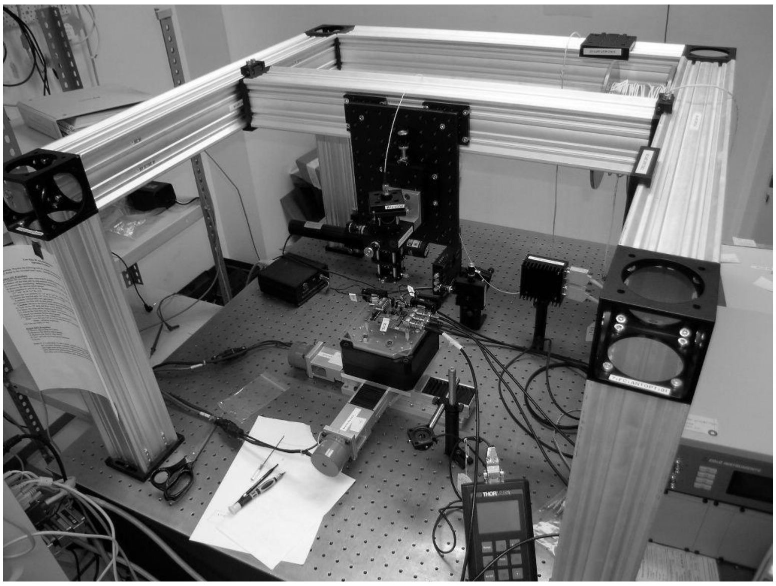


Figure 1: Picture of the measurement station. The nanometric precission cube is placed on a two XY linear stage. The beam is delivered through an optical fiber.

The different spectral ranges where optical antennas respond need different approaches and specifications. In this contribution we show our effort focused on the near infrared and visible range. Here the wavelength is shorter than in the medium or far infrared, making the mechanical stability and movement accuracy a must in the measurement set-up. Contrary wise, medium and far infrared characterization stations need to face those problems associated with the few available light sources, optics, polarization controlling systems, beam characterization elements, etc. With the accumulated experience obtained from the measurement in the medium infrared we have designed and built a measurement station (see Figure 1) as follows:

Light delivering system: In the visible and near infrared there are available a myriad of semiconductor light sources typically developed for optical communication systems. We have chosen this kind of sources with proved performance. The output of the laser is injected on a monomode fiber that is in charge of the spatial filtering of the laser beam. After collimation, the state of polarization is transformed into the desired state and finally focused on the detector itself. The laser source can be electronically modulated by several means, well in the power supply or at the device input by using appropriate signal generators (see Figure 2).

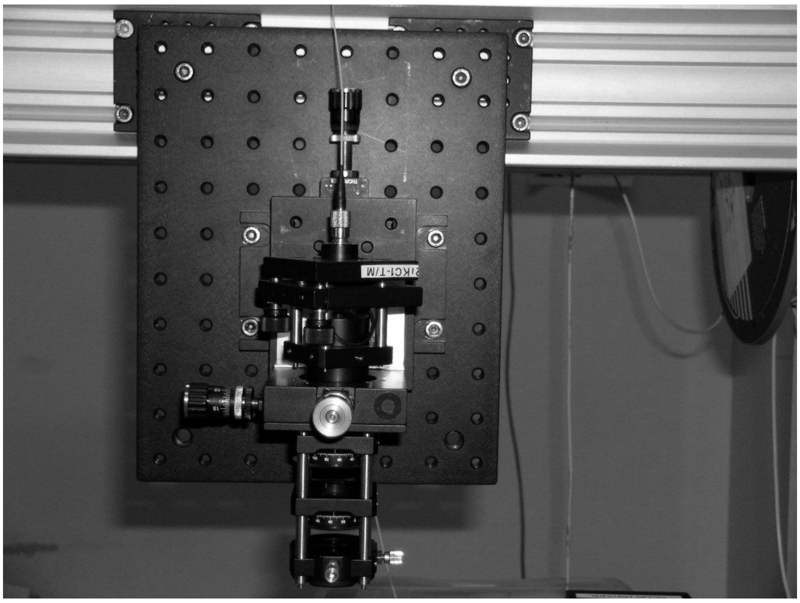


Figure 2: Light delivering system. The polarization state is controlled by several phase plates. The beam is focused by a very short focal length lens.

Signal conditioning system: an optical antenna coupled to a bolometer or a Metal-Oxide-Metal junction, produces a variation of a bias voltage that is proportional to the received irradiance. Due to this detection mechanism, 1/f noise is present and some modulation has to be place to minimize that noise source. On the other hand, optical antennas are quite sensitive to electric discharge damage, and the set-up to operate devices at the laboratory level need to be careful. The team at the Infrared Systems Laboratory in the School of Optics /CREOL has accumulated a large experience on this and has provide us with specifically designed biasing, conditioning, and amplification circuitry and electronics. The optical antennas, that have been also prepared at the School of Optics / CREOL, are attached to this electronic subsystem. When characterizing some other type of detector, the signal conditioning system may vary and be adapted to the intrinsic specifications of the given case.

Movement: The high spatial resolution needed to characterize the spatial frequency of optical antennas is achieved by using a piezo-electric cube with a total range of $200\times200\times200$ μm^3, a resolution of 5 nm, and repetitivility of 50 nm along the whole range. This element is placed on two axis linear DC travelling stages having a resolution of 0.25 μm and 1 μm of repetitivility along 100 mm travel range. These DC stages are used to make a low resolution movement in order to roughly place the device under the light spot. Once this setting is made, the cube having nanometric resolution is in charge of the high resolution measurement. When the measurement of interest is the time response of the devices, the movement elements are used to place the detectors under the maximum irradiance spot. Then, it is locked there to proceed with the measurement.

Control:- We can distinguish between those elements that currently need a manual adjustment and those systems controlled by computer.

The parameters that are manually adjusted are:

- A rough, low resolution (10 μm), movement along the axis of propagation of the light to approximately place the focused spot on the detector.
- The adjustment of the state of polarization of the incident light.

On the other hand the computer is in charge of controlling the following elements:

- The power supply and the temperature controller of the semiconductor laser,
- The modulation elements and systems: modulation is basic to avoid 1/f noise when characterizing the spatial frequency. When the temporal response characterization is made, the frequency of modulation is also changed and controlled to provide the dependence of the device with the temporal frequency.
- The measurement of the biasing voltage on the optical antenna
- The lock-in amplifier control and measurement: this element is tuned and depends on the output given by the modulation element. When mechanical modulation is chosen, the chopper is attached to and controlled by the lock-in amplifier.
- The low resolution and high resolution movements along the three spatial directions.
- The scanning strategies and parameters to automatically register the output of the detectors.

All these elements and subsystems have needed a dedicated adjustment and calibration. For example, the polarization state depends on the mechanical stability of the optical fiber attached to the semiconductor laser. The location and position of the polarization controlling elements (2 $\lambda/4$ and 1 $\lambda/2$ plates) is monitorized and adjusted when some changes involving the laser source and fiber are made.

This measurement station is complemented by calibrated power meters within the spectral range of the sources, and by some other elements needed to characterize the incoming laser beam.

3.- Testing procedure and evaluation.

In this section we explain how the spatial responsivity is measured by using the previously described set-up.

3.1- Beam characterization

The response of the detector is the integration of its spatial response multiplied by the irradiance distribution actually falling on it. When a two dimensional scan is made by moving the detector or the light beam, the result is the convolution between the spatial response of the detector and the spatial distribution of the incident irradiance. If the detector spatial response area is much broader than the irradiance distribution, the output of the scan can be taken as a good approach to the spatial response of the detector. However, optical antennas can not be treated like this. Optical antennas are typically smaller, or even, much smaller than the irradiance distribution. Then, the use of some kind of deconvolution algorithm is necessary. However, to make a sound de-convolution, the incident irradiance distribution needs to be know with appropriate resolution. Unfortunately, the usual methods to characterize light beam by analyzing their spatial distribution falling on an array, are of no use in these cases. The spot to be characterized is about the size of the individual elements of a focal plane array. Some other strategies are then at work. They are typically based on knife-edge techniques. Here, the lateral resolution can be as good as the movement of the knife edge. However, the result is an integrated value that has to be treated afterwards. A fairy good beam characterization is made by performing two orthogonal knife-edge measurements at different planes along the propagation of light. The first practical result of these measurements is the location of the narrowest spot. These measurements are then included within a fitting algorithm that looks for the irradiance distribution that would fit the measured data. The algorithm is fed with a model of the beam that includes a Gaussian distribution, the Fraunhofer diffraction produced by the optical elements, and some aberrations typically encountered in these situations. These aberrations are spherical, and coma.

4.- Evaluation of the uncertainties and error in the measurement procedure.

The validation of the measured data obtained from the characterization station will depend on the quantification of the contribution of the differents parts in the measurement chain to the total uncertainty and error in the final result. To properly identify these sources of error we first begin with the description of the measurement protocol.

Spatial location and orientation of the optical antennas:

The optical antennas are mounted on a chip carrier. This chip carrier is now placed and connected onto a socket of the biasing and amplification electronic circuit. This circuit is attached to the nanocube by using four screws. The total uncertainty in the angular misalignement between the symmetry of the optical antenna and the coordinate system for the movement of the antenna is expressed as $\Delta\phi$.

Spatial location of the light spot.

When characterizing the spatial response of the detectors it is necessary to focus the light spot by using focalization optics. The light delivery system is made of a monomode optical fiber. The connector of the fiber is a FC connector that is attached to a collimation set. The collimated beam crosses the polarization controlling elements. These elements are adjusted to be perpendicular to the propagation axis by using high precision optical bench components. The light arrives to the focalization unit that produces a spot that is assumed to be nearly Gaussian. The deviation of the Gaussian character will be modelled and taken into account by using a separate procedure. The Gaussian spot has a size ω_0 and a focalization range of $z_R=\pi\omega_0^2/\lambda$. The antenna has to be placed right in the maximum of the irradiance of this quasi-Gaussian spot. The location of the antenna under this spot is made by successive scanning measurements of the signal given by the antenna until reaching the plane where the maximum signal is achieved. The location of this plane is made by using two stages. One of them is driven manually and has an uncertainty of 10 microns. The other one is driven automatically and has an uncertainty given by the repetitivility of the nano cube module Δz. The lateral location of the antenna under the spot is also done by combining a low precision movement and a high precision one. The uncertainty is the same than along the Z direction $\Delta x=\Delta y=\Delta z$.

Setting of the state of polarization.

The optical system in charge of the illumination of the antenna is also formed by the polarization controlling elements (see Figure 2). The output of the monomode fiber is an arbitrary elliptical state of polarization that mainly depends on the mechanical curvatures of the fiber itself. To prevent these curvatures, the fiber is enclosed on a rigid tube that fixes the mechanical situation of the fiber an stabilizes the polarization state observed at the output of the fiber. This elliptical state is transformed to a linear state of polarization by using a $\lambda/4$ and λ /2 achromatic plates. The angular location of these plates is fixed with an uncertainty $\Delta\theta$. The linear state is checked by using standard polarization filters and a power meter. In those cases where the state of polarization is set as linear, the light goes directly to the focusing element. When other state of polarization is required, another achromatic λ /4 plate is placed behind the λ /2.

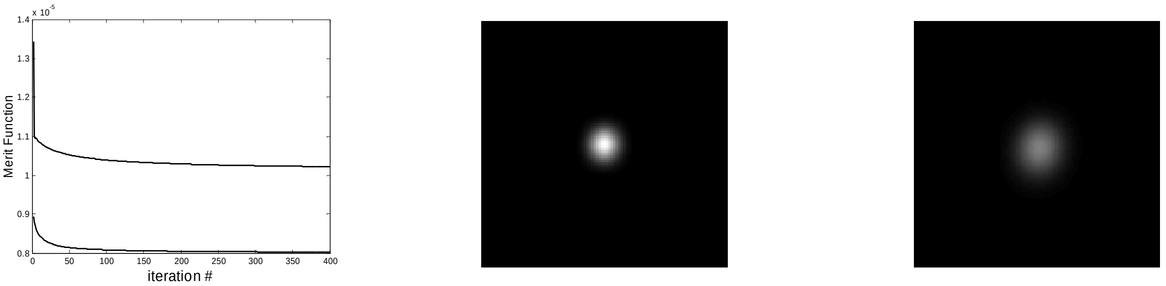
Characterization of the irradiance distribution.

The application of the deconvolution algorithm requires a precise knowledge of the irradiance distribution. This mapping can be made by several methods. If some image acquisition systems are available at the used wavelength, these are located to register the light distribution at several planes. These planes are separated by a given distance Δz that is controlled manually or automatically. The fitting of the evolution of the irradiance distribution with the expected evolution of a Gaussian beam is made. The discrepancies are treated and modelled by using numerical techniques that incorporate a given aberration composition. On the other hand, at this point, it is also possible to actuate on the collimation and focalization optics to improve the quality of the beam.

If the wavelength of the beam is out of the detection range of the available image acquisition system, then the characterization has to be done by using scanning methods. Among them, the knife edge scanning method is the simplest and provides results with the resolution of the translation stages. Unfortunately knife-edge scanning methods provides integrated measurements and the irradiance map can not be easily found. To improve the validity of the results the experimental data are compared and fitted with a model of a Gaussian beam affected with a given composition of aberrations.

Conditioning and deconvolution of the data

The experimental data are registered by a two dimensional scanning procedure along a window $l_x \times l_y$ with an spatial step $\Delta\, l_x$ and $\Delta\, l_y$ and an uncertainty $\Delta\, x$ and $\Delta\, y$. The signal is obtained from the electronic amplification circuit. Previously, the optical irradiance is modulated at a given frequency by driving the power supply with a signal generator. The modulation is made in such a way that the current fed to the laser source commute between two values, one of the them is clearly below the threshold current and the other is clearly above. Both the modulation signal and the modulated output from the antenna are combined in a dual lock-in amplifier. The reading in the amplifier is registered and averaged along a time window at each point of the scan. All this acquisition procedure is automatized and controlled by computer. The time necessary for a complete scan will depends on the number of points of the scan and the averaging time at each point. Typical measurement times are of about 100 minutes.



Evolution of the Merit Function for two noise levels

Result of the deconvolution without noise

Result of the deconvolution for a spatial white noise level of 10%

Figure 3: The result of the deconvolution algorithm is affected by the level of the noise. The main effect is the widening of the deconvolution result.

The obtained signal is the convolution of the spatial response of the device with the irradiance distribution falling on the detector. On the other hand, inhomogeneities of the measurement data can be somehow compensated by averaging a collection of measurement. The averaged scan is included within an iterative deconvolution algorithm that is controlled by a merit function that is minimized along the process. In Figure 3 we have plotted the evolution of the Merit Function that monitorizes the results of the iterative algorithm as a function of the spatial noise level. The result is that the deconvolution widens as the noise increases. This can also be checked by analyzing the map of the standard deviation as a function of noise. The results are shown on Figure 4. The beam used in the deconvolution is that one previously modelled and characterized. The deconvolution result is also checked to assure the goodness of the data.

For optical antennas, the signal can be split in two parts. One of them is of thermal nature and it does not depend with the polarization state of the incoming radiation. The other is polarization sensitive and is related with the energy actually coupled to the metallic antenna structure. In most of the cases, the characterization efforts are on this part. To extract it from the experimental data it is necessary to obtain two measurements, one of them is prepared to be only the thermal response. The state of polarization necessary is customized and adapted to that case. The other measurement is a map that contains both the polarization response and the antenna response. This antenna response is them obtained by substracting both experimental data.

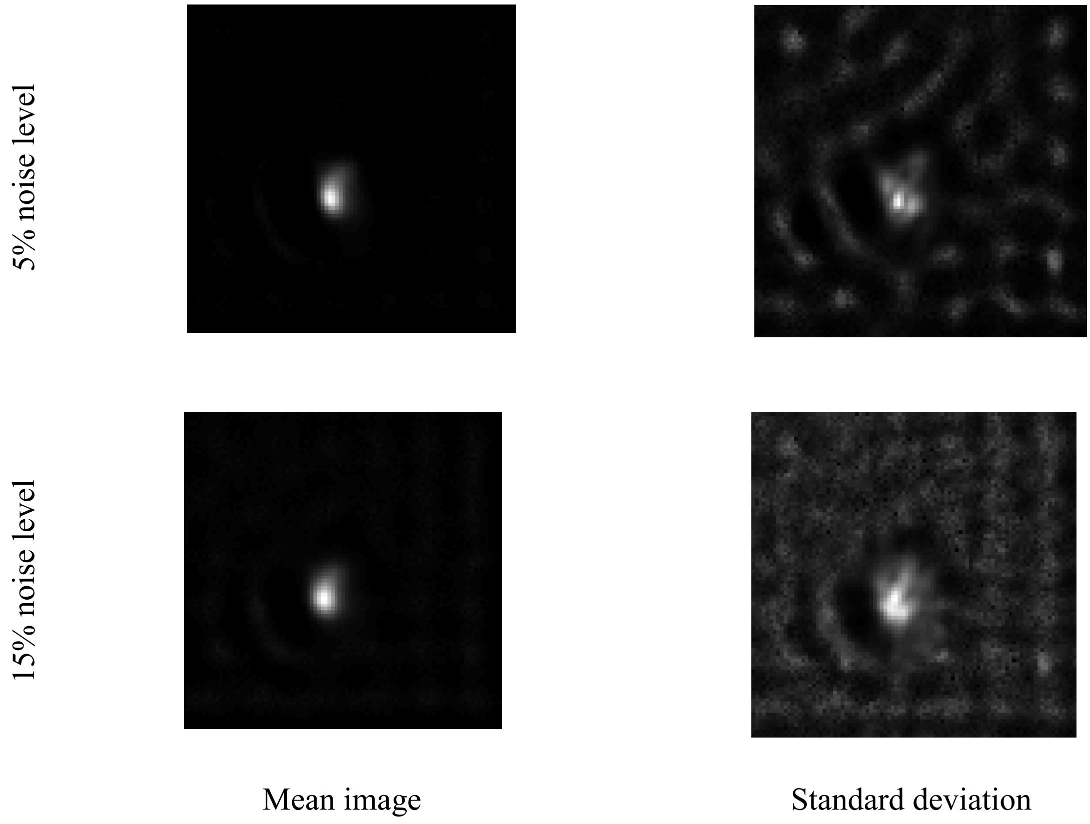


Figure 4: When the spatial noise is randomly distributed it can be filtered by a simple averaging effect. However, the corresponding standard deviation grows with the noise level.

5.- Conclusion

An appropriate characterization of optical antennas requires the use of scanning systems with sub-wavelength spatial resolution. The procedure for making such a characterization is based on a well-defined protocol where the different contributions of the experimental uncertainties need to be taken into account. In this contribution we show the practical set-up of a measurement station of this kind. We have designed the system using optical fiber systems and diode laser sources. This choice is related with the goal of having a proper characterization of optical antennas in the visible and near infrared range. However, the proposed measurement station can be also used to characterize any other type of detector in the applicable wavelength range.

The dependence of the deconvolution process with respect to the noise of the measured data is analyzed. As it should be expected, the presence of the noise degrades the results of the deconvolution algorithm. If the noise is randomly distribution it could be filtered out by a simple averaging process. The complete analysis of the uncertainties of the measurement station is necessary to assure the trazability of the results.

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