A Near Field Microscope in the Tera-hertz Region

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Abstract. This paper reports the study of a experimental project for two near field microscopes to operate in the Tera-Hertz (THz) region of the electromagnetic spectrum. The first design is suited more properly for the millimetre wave region, while the second is addressed to shorter wavelengths, typically below one millimetre.

Key words: Microscopy, near-fields generation, Tera-Hertz radiation

1. Introduction

Since the early works on the near field generation by diffraction from sub-wave-length apertures [1], the importance of the exploitation of such electromagnetic field was clear. At that time it was necessary to couple guided radiation through different waveguides by means of holes realized on their walls. In the early '80 [2] a renewed interest arose on evanescent fields in order to increase spatial resolution in optical microscopy. The success of the Scanning Near-field Optical Microscopy (SNOM) in the visible and near infrared spectral regions, has pushed the research in the direction of the increase the imaging spatial resolution also at different wavelengths. Some pioneering works [3, 4] have demonstrated the feasibility for the operation of a SNOM device in the millimetre and sub-millimetre wave range. The difficulty for the realization of a SNOM in the THz region lies in the fact that there have been a lack of sources in this spectral range since the coming of the THz-emitters and of the Free Electron Lasers [5]. Moreover there is an additional difficulty related to a lack of specific technology for the propagation and manipulation of the THz radiation beam, because this wavelength region is in between the microwave region, where the waveguide technology is well established, and the infrared region where the lenses and mirrors technology is used.

In the next paragraph the theory at the basis of the project is presented briefly, while in the third one the design of the device to be used at the Frascati FEL facility is illustrated.

Figure 1. Equivalent principles geometries: a) transverse coupling; b) longitudinal coupling.

2. Theory

The theory for the evaluation of the electromagnetic field diffracted from an aperture with dimensions smaller than the wavelength of the incident field can be derived following the Bethe approach [1]; the presence of a waveguide as a propagation medium allows the use of standard theories of mode expansion in cavities [6] and at the end the overall logical process can be summarized as follows:

1. The first step is the enunciation the so called *equivalent principles* with which is possible to evaluate the field irradiated from a cavity to a second one coupled with it by a hole. There are two possible coupling geometries as illustrated in Figure 1; in the transverse geometry (Figure 1a) the fields E_2 and H_2 are those generated by the equivalent electrical current: $J = n \wedge H_0$. In the case of a longitudinal coupling (Figure 1b) the fields E_2 and H_2 are irradiated by an equivalent fictitious magnetic current: $J_m = -n \wedge E_0$.
2. The second step is to perform a mode expansion of the field as usually done inside metallic waveguides or cavities. Because of the presence of a hole the expansion must take into account both propagating and evanescent modes. In a general way we can write $E = E^+ + E^-$ and $H = H^+ + H^-$ where:

$$E^\pm = \sum_\lambda A_\lambda^\pm E_\lambda^\pm \quad ; \quad H^\pm = \sum_\lambda A_\lambda^\pm H_\lambda^\pm \quad (1)$$

and where $A_\lambda^\pm$ represents the expansion coefficients for the mode λ .

3. The expansion coefficients can be calculated by means of the Poynting theorem that we recall in the following form: $\int_S n \cdot (E \wedge H_\lambda^\mp - E_\lambda^\mp \wedge H) da = \int_V J \cdot E_\lambda^\pm d^3x$ where J is the current density representing the source contained in the volume V . The integration can be performed by means of (1) and leads to the following result [7]:

$$A_\lambda^\pm = \frac{Z_\lambda}{2} \int_V J \cdot E_\lambda^\mp d^3x + \frac{Z_\lambda}{2} \int_{Aperture} J_m \cdot H_\lambda^\mp da \quad (2)$$

where Z_λ indicates the impedance of the λ -th mode in the waveguide. The second term of (2) indicates that the aperture, in the case of longitudinal coupling, acts as a source expressed by the current density J_m .

4. The fourth step consist in making the assumption that the hole dimensions in the waveguide are much smaller than the radiation wavelength. This hypothesis allow us to perform a Taylor expansion of the fields in the hole. If we limit the expansion to the dipole contribution we obtain: $H_\lambda(x, z) = H_\lambda(0) + r \cdot \nabla H_{\lambda|0}$. Substituting the expansion in eq. (2) we obtain:

$$A_\lambda^\pm = \frac{Z_\lambda}{2} \left[H_\lambda^\mp(0) \int_{Aperture} J_m da + \int_{Aperture} (r \cdot \nabla H_\lambda^\mp) \cdot J_m da \right] \quad (3)$$

After some algebra it can be demonstrated that the first term of (3) can be associated to a magnetic dipole moment: $\vec{M} = \vec{r} \int_{Aperture} \vec{n} \cdot \vec{H} da$. In the same way, to the second term of eq. (3) it is associated an electric dipole moment: $\vec{P} = -(\epsilon_0/2)\vec{n} \int_{Aperture} \vec{r} \cdot \vec{E} da$.

It is worth to stress that the electric field in P is tangential to the hole plane while the magnetic field in M is perpendicular to the hole plane itself. Those fields are unknown and must be related to the known electric and magnetic fields in the waveguide. Because of their mathematical derivation the dipole moments must be proportional to the fields strengths. The proportionality factor is the polarizability tensor which value depend on the size and shape of the hole. The result at the end is that the polarizability tensor and thus the dipoles M and P can be derived as in magnetostatic and electrostatic theories. The results are: $\vec{P} = \epsilon_0 \frac{r_0^3}{3\pi} \vec{E}_0$ and $\vec{M} = -\frac{2r_0^3}{3} \vec{H}_0$ where E_0 is the normal electric field of the mode propagating in the waveguide and H_0 is the tangential magnetic field of the same mode. The electric and magnetic fields generated by the electric dipole moment beyond the hole are (see Figure 2 for the geometry considered):

$$\begin{aligned} \vec{E}(\vartheta, \phi, r) &= \left[\vec{n}(\vartheta, \phi) \cdot (3\vec{P} \cdot \vec{n}(\vartheta, \phi)) - \vec{P} \right] \frac{1}{4\pi \epsilon_0 r^3} \\ \vec{B}(\vartheta, \phi, r) &= ik_0 (\vec{n}(\vartheta, \phi) \times \vec{P}) \frac{c\mu_0 \epsilon_0}{4\pi r^2} \end{aligned} \quad (4)$$

Figure 2. Geometry of the hole in the waveguide.

where k_0 is the wave-vector of the radiation. The fields generated by the magnetic dipole can be derived by eq. (4) making the following substitutions: $\vec{E} \rightarrow \vec{B}$; $\vec{B} \rightarrow -\vec{E}$; $\vec{P} \rightarrow \vec{M}$.

3. Experiment Design

The theory reported in the previous paragraph is applied to an experimental device to be realized at Frascati in order to operate at the compact FEL facility [8] in the millimetre wave region. The basic idea is to inject the FEL output radiation at 2.6 mm in wavelength into a waveguide (WR42 $4.318 \text{ mm} \times 10.06 \text{ mm}$) in the side-wall of which a hole is realised in a position where the maximum of the electromagnetic field in the guide is present. The hole diameter is taken to be 1/10 of the wavelength ($r = 0.13 \text{ mm}$). The field radiated by the hole can be calculated by means of the eq.(4) and the power associated with it is reported in Figure 3. This is the field that interacts with the sample that will be placed just over the hole and scanned in the X-Z plane. The amplitude of the electromagnetic field transmitted by the different parts of the sample will reconstruct the image of the sample itself in the millimetre wave range but with a spatial resolution of about 1/10 given by the hole size. A sketch of the layout is reported in Figure 4.

This transmitted electromagnetic field must be extracted from the surface of the sample by means of a device that is capable to convert the ‘evanescent’ nature of

Figure 3. Energy distribution of the electromagnetic field radiated by the hole. The numbers indicate the fraction of energy calculated respect to the one incident on the hole. a) distribution in the Y-Z plane; b) distribution in the X-Z plane.

this field into a propagating one. The optical element that can be used is a cone having an aperture of the same size and shape of the field generated by the hole. This size, in our case, can be deduced in Figure 3 b) and corresponds to a starting radius of $r = 0.2 \text{ mm}$. The diffracted field at the surface of the waveguide couples with the modes of the cone; the most efficient coupling can be demonstrated to be with the TM modes, but a small percentage of the energy associated to the near field, will propagate also with the TE modes [9].

Figure 4. A sketch of the experimental layout.

In conclusion the cone, that acts as a collector, converts the reactance energy associated to the evanescent field into propagating energy, and transports the information of the sample transmission, at the sub-wavelength resolution, to the detector.

The realisation of a SNOM device in the THz region will improve the knowledge in many fields of research, like solid state physics; but the enormous importance that imaging is gaining in biological science tells us that this technology will be one of the tools for the future research in the future.

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References

1. Bethe, H.A.: Theory of Diffraction by Small Holes, *Phys. Rev.* **66** (1944), 163–182.
2. During, U., Pohl, D.W. and Rohner, F.: Near-Field Optical-Scanning Microscopy, *J. Appl. Phys.* **59** (1986), 3318–3325.

3. Keilmann, F., Weide, D.W., Eickelkamp, T., Merz, R. and Stockle, D.: Extreme Sub-Wavelength Resolution with a Scanning Radio-Frequency Transmission Microscope, *Opt. Commun.* **129** (1996), 15–18.
4. Knoll, B. and Keilmann, F.: Near Field Probing of Vibrational Absorption for Chemical Microscopy, *Nature* **399** (1999), 134–137.
5. Doria, A., Gallerano, G.P. and Giovenale, E.: Free Electron Broad-Band THz Radiator, *Nucl. Instr. and Meth. A* **483** (2002), 461–465.
6. Collins, R.E.: *Field Theory of Guided Waves*, McGraw-Hill, New York, 1960.
7. Jackson, J.D.: *Classical Electrodynamics*, Wiley & Sons, New York, 1975.
8. Ciocchi, F., Bartolini, R., Doria, A., Gallerano, G.P., Giovenale, E., Kimmitt, M.F., Messina, G. and Renieri, A.: Operation of a Compact Free-Electron Laser in the Millimeter-Wave Region with a Bunched Electron Beam, *Phys. Rev. Lett.* **70** (1993), 928–931.
9. Coniglio, A.: *Studio e Progettazione di un Dispositivo per Microscopia a Campo Prossimo nella Regione Spettrale del Tera-Hertz*, Thesis Publication, University of Rome ‘Roma Tre’, Rome, 2002.