Double Application of Superconductor and Photonic Material on Antenna Array

HUMBERTO CÉSAR CHAVES FERNANDES AND LUIZ PAULO RODRIGUES
Department of Electrical Engineering - Federal University of Rio Grande do Norte, Natal/RN-BRAZIL-59.072-970, P. O. Box 1583, Tel/Fax: +55 84 2153731

Abstract- The combined use of photonic and superconductor materials can be applied to millimeter waves, microwaves and planar antenna frequencies as well as planar arrays. The superconductor patch antenna is analyzed according theories: BCS theory, London equations and Two-Fluid model. The full wave Transverse Transmission Line (TTL) method is used for the analysis of rectangular microstrip patch with PBG substrate. In this method a set of equations that represents the electromagnetic fields in the x and z direction as function of the fields in the y direction are obtained. The inclusion of superconductor strip is made using the resistive complex contour condition. The array factor is calculated for the planar array. The effect of the phase variation is analyzed in planar microstrip antenna, resulting in a phased array. Computer simulations of the resonant frequency and radiation pattern for some phase excitation in a rectangular array are shown.
Key-Words: -TTL method, PBG, Antenna array, resonator.

1 Introduction

The superconductivity phenomenon was discovery of by Heike K. Onnes in 1911 [1], when he cooled down the purified mercury to the liquid helium temperature (4.2 K) and the resistance abruptly dropped to zero. Below this temperature mercury became superconductive [1]. These low-temperature superconductors (LTS) have its limited use because they operate in near liquid helium temperatures. The high-temperature superconductors (HTS) that operate in liquid nitrogen temperature have many advantages as low loss, low noise, low power consumption and circuit miniaturization [1], [6]-[8].

The phased antenna array is composed of a group of individual radiators that are distributed and oriented in a linear or two-dimensional spatial configuration. The magnitude and phase excitations of each radiator can be individually controlled to form a field radiation of any desired shape in space. The position of the field in space is controlled electronically by adjusting the phase of the excitation signals at the individual radiators. Phased antennas array have properties that make the best choice for directivity in modern mobile communication. They are well suited for use in the microwave frequencies. In the Fig. 1 a planar microstrip array of 3x3 elements is shown. The microstrip antenna consists of a radiating structure spaced a small fraction of wavelength (0.01 to 0.05 free-space wavelength) above a conducting ground plane. Antenna arrays of this type have found applications where low cost, lightweight, reduced dimensions, and high efficiency are necessary requirements for wireless communications and can be used in many applications over the broad range of frequencies.

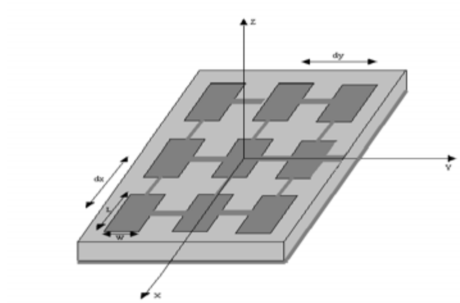


Fig.1. Planar antennas array of 3x3 elements.

Usually the radiation pattern of a single element is relatively wide, and each element provides low values of directivity. In many applications it is necessary to design antennas with very high directive characteristics to meet demands of long distance communications using antenna array.

Otherwise, the presence of photonic materials as substrate in antennas, has some good characteristics such as, suppression of light spontaneous emission and suppression of surface waves, allowing the application in planar antenna array. The PBG structure is added as dielectric material in antenna that impede the propagation of electromagnetic waves in some frequency, producing photonic band gap (PBG).

Photonic band gap materials are similar to semi-conductors in that they exhibit gaps in the energy structure for photons (instead of electrons). In a photonic crystal if a photon has energy in the photonic band gap it will be unable to propagate through the material no matter the direction of the light. In this work an elaborate analysis using the full wave Transverse Transmission Line method, which provides efficient and concise results is applied to the planar antennas array with PBG substrate and superconductor patch. Various applications using the TTL method has been presented by H.C.C. Fernandes et al [2]-[5].

2.Theory

2.1 Superconductor Material

There is not a satisfactory quantum theory for the superconductivity, however a very used microscopic theory is the BCS theory [6]-[8] and the macroscopic theories more used is the Two-Fluids Model and the London Equations [9]-[13]. The superconductor material presents some experimental characteristics, such as: null resistivity; persistent current; magnetic field effect; flow exclusion (Meissner effect); frequency effect and isotope effect [6]-[8].

2.1.1 BCS Theory of Superconductivity

The base of the superconductivity quantum theory was developed in 1957 by the works of Bardeen, Cooper and Schrieffer. The formulation of the theory BCS includes among other phenomenons [6]-[8]:

a) An attractive interaction among electrons can be led to a fundamental state separate from excited states by a energy lacuna that separates the superconductors electrons below the lacuna of the normal electrons. The critical field ($\vec{H}_c$), the thermal properties and many other electromagnetic properties are consequences of that energy lacuna.

b) The penetration depth (λ_l) and the coherence length (ξ), that it is a measure of distance of the lacuna, appear as natural consequences of the BCS theory. The London equation is obtained for magnetic fields that vary slowly in the space. In this the Meissner effect is obtained in a natural mode.

c) The BCS theory predicts the critical temperature of an element or alloy. There is a paradox: as larger the resistivity in the ambient temperature, greater will be the probability that the metal is a superconductor when cold.

The BCS theory attributes the superconductivity effect to a pair of electrons opposite spin, called Cooper pair.

2.1.2 London Equations

It can be made an approach in the electrodynamics equation, staying the same to the permeability (μ) and the permittivity (ε), and being used the hypothesis that the null resistivity leads to the acceleration equation as presented below [6]-[8]:

$$e\vec{E} = m\frac{d\vec{v}}{dt} \qquad (1)$$

$$\Lambda\frac{\partial \vec{j}}{\partial t} = \vec{E} \qquad (2)$$

$$\Lambda \nabla x\, \vec{j} = -\vec{B} \qquad (3)$$

where

$$\vec{j} = ne\vec{v} \qquad (4)$$

$$\Lambda = \frac{m}{ne^2} \qquad (5)$$

Of from the equations above can be derived the following equation

$$\nabla^2 \vec{B} = \frac{\vec{B}}{\lambda_l^2} \qquad (6)$$

where

$$\lambda_l^2 = \frac{mc^2}{4\pi ne^2} \tag{7}$$

λ_l is the London penetration depth that measures the penetration of the magnetic field in the superconductor, "m" is the particle mass, "n" is the particles quantity, "e" is electron charge, "c" is the light speed in vacuum and "v" is the carrier speed of the particle.

Equation (6) explains the Meissner effect, not allowing a uniform solution in the space, not could exist a uniform magnetic field into a superconductor. The solution of (6) is indicated below:

$$\vec{B}(x) = \vec{B}_0\, e^{-x/\lambda_l} \tag{8}$$

A magnetic field applied will penetrate approximately in a fine film in way uniform, if the film thickness is very small than λ_l the Meissner effect is not complete.

2.1.3 Two-Fluid Model and Surface Impedance

There is not a macroscopic theory that describes with accuracy the electric properties of the superconductor to temperatures below the critic. The model more used for those temperatures is the two-fluids model that has been applied with success. The theory BCS is very used in superconductors with low critical temperature, while the two-fluids model is used in superconductors with high critical temperature and for materials with weak magnetic field.

The complex conductivity obtained of the two-fluids model is expressed in (9), while for a superconductor of the type II, the advanced two-fluids model is used, being the conductivity expressed in (10) [9]-[12],[14]:

$$\sigma = \sigma_n\left(\frac{T}{T_c}\right)^4 - j\left(\frac{1}{\omega\mu\lambda_{ef}^2(T)}\right) \tag{9}$$

$$\sigma = \sigma_n\left(\frac{T}{T_c}\right)^{1/2} - j\left(\frac{1}{\omega\mu\lambda_{ef}^2(T)}\right) \tag{10}$$

where σ_n is the conductivity for the superconductor in its normal state; λ_{ef} is the effective penetration depth of the magnetic field for the normal and advanced two fluids model [9]-[12],[14]:

$$\lambda_{ef}(T) = \lambda_{ef}(0)\left(1-\left(\frac{T}{T_c}\right)^4\right)^{-1} \tag{11}$$

$$\lambda_{ef}(T) = \lambda_{ef}(0)\left(1-\left(\frac{T}{T_c}\right)^{\alpha}\right)^{-1/2} \tag{12}$$

where $1,4 < \alpha < 1,8$ [14].

In this theory the effective penetration depth is larger than the London penetration depth for materials of high Tc due to irregularities of the material. The effect of another mechanisms of losses, as the surface contours losses and residual losses are frequently included in σ_n.

In spite of those uncertainties the two-fluids model is still a powerful empiric tool and it supplies important qualitative results.

The surface impedance of a dielectric material, a metal normal and a superconductor are shown in Fig. 2 [13].

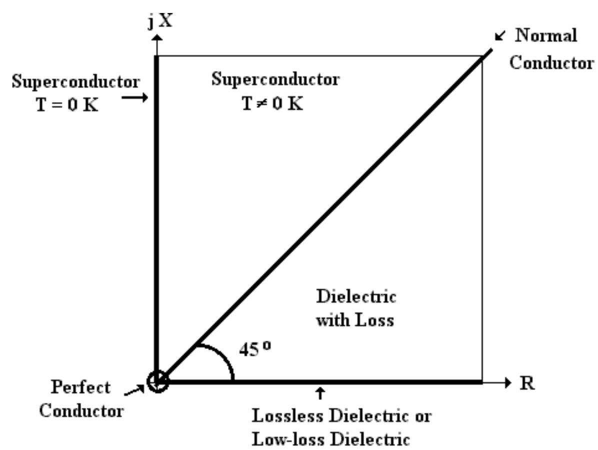


Fig. 2. Surface impedance of a dielectric, normal metal and a superconductor.

The surface impedance of a dielectric material losssless or of low-losses it is real positive, the surface impedance of a normal metal meets along the line of 45° and for a superconductor, that can be also treated as negative dielectric (in agreement with some authors) the surface impedance meets in the positive imaginary axis. In the limit case in that the conductivity (σ) tend to infinite in the conductor or the dielectric constant (ε_r) tend to infinite in the dielectric, the surface impedance will tend to zero. When they approach of the origin is not possible to distinguish macroscopically the perfect conductor of superconductor. For a conductor the inductive reactance is the same to the resistance however for the superconductor the part reactivates it is larger than the resistive part. The surface impedance is given by:

$$Z_S = \left|\frac{\vec{E}_T}{\vec{J}}\right| = \sqrt{\frac{j\omega\mu}{\sigma}} \qquad (13)$$

where

$$\vec{J} = \int_0^t \vec{J}_v \, dz \qquad (14)$$

being considered the effective penetration depth (λ_{ef}) larger than the thickness of the superconductor film can approach the surface impedance for

$$\vec{J} = \int_0^t \vec{J}_v \, dz = \vec{J}_v \, t \qquad (15)$$

$$Z_s = \left|\frac{\vec{E}_T}{\vec{J}}\right| = \left|\frac{\vec{E}_T}{\vec{J}_v t}\right| = \frac{1}{\sigma t} \qquad (16)$$

where $\vec{J}_v$ is the uniform volumetric current density and t is the thickness of the superconductor sheet.
For a fine superconductor sheet, or normal conductive strip, where the internal field of the strip is approximately uniform, the tangential component of the electric field is given for:

$$\vec{E}_T = Z_s \vec{J}_T \qquad (17)$$

where ET is the tangential component of the field electric in the strip and JT is the surface current density.

2.2 TTL Method

Considering the microstrip antenna resonator of Fig. 3, the equations that represent the electromagnetic fields in the **x** and **z** direction as function of the electric and magnetic fields in the **y** direction are obtained applying the TTL method.

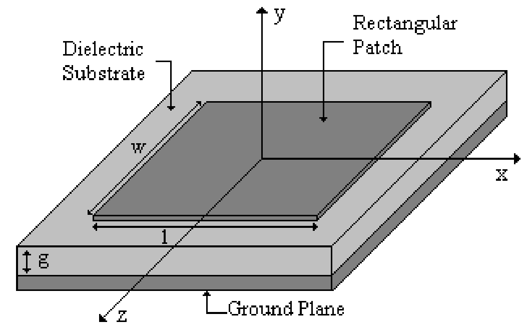


Fig 3. Microstrip patch antenna resonator

Starting from the Maxwell's equations and after various algebraic manipulations the general equations for the structure in the Fourier Transform Domain-FTD are obtained, for the **x** direction as:

$$\tilde{E}_{xi} = \frac{1}{\gamma_i^2 + k_i^2}\left[-j\alpha_n \frac{\partial}{\partial y}\tilde{E}_{yi} + \omega\mu\beta_k \tilde{H}_{yi}\right] \qquad (18)$$

$$\tilde{H}_{xi} = \frac{1}{\gamma_i^2 + k_i^2}\left[-j\alpha_n \frac{\partial}{\partial y}\tilde{H}_{yi} - \omega\varepsilon\beta_k \tilde{E}_{yi}\right] \qquad (19)$$

and for **z** direction as:

$$\tilde{E}_{zi} = \frac{1}{\gamma_i^2 + k_i^2}\left[-j\beta_k \frac{\partial}{\partial y}\tilde{E}_{yi} - \omega\mu\alpha_n \tilde{H}_{yi}\right] \qquad (20)$$

$$\tilde{H}_{zi} = \frac{1}{\gamma_i^2 + k_i^2}\left[-j\beta_k \frac{\partial}{\partial y}\tilde{H}_{yi} + \omega\varepsilon\alpha_n \tilde{E}_{yi}\right] \qquad (21)$$

where i = 1, 2 are the regions dielectric of structure, $\gamma_i^2 = \alpha_n^2 + \beta_k^2 - k_i^2$ is the propagation constant in **y** direction, α_n is spectral variable in **x** direction, β_k is spectral variable in **z** direction, $k_i^2 = \omega^2\mu\varepsilon = k_0^2\varepsilon_{ri}^*$ is wave number of i*th* dielectric region and $\varepsilon_{ri}^* = \varepsilon_{ri} - j\frac{\sigma_i}{\omega\varepsilon_0}$ is the relative electric permissive of material, α_n is the spectral variable, k is the wave number , $\Gamma=\alpha+j\beta$ is the complex propagation constant, α is the attenuation constant, β is the phase constant and γ is the propagation in the y direction in the FTD.
The inclusion of the superconductor patch is made using the resistive complex boundary condition.

That condition relates the electric field inside of the superconductor strip with the current density, through surface impedance

$$\tilde{E}_T = Z_S \tilde{J}_T \qquad (22)$$

where $\tilde{E}_T$ and $\tilde{J}_T$ are the electric field and the tangential current density to the superconductor strip, respectively, and Z_S is the surface impedance, defined for:

$$Z_S = \frac{1}{\sigma_{S2} t_2} \qquad (23)$$

σ_{S2} is the conductivity of the superconductor strip and t_2 the thickness of the strip.
After the application of the boundary conditions, the Moment method is used to eliminate the electric fields and to obtain the homogeneous matrix equation for the calculation of the complex resonant frequency. The roots of this matrix are the real and imaginary resonant frequencies.

2.3 Phased Array

To provide radiation in two angular dimensions, a planar array of radiating elements is used. The complete field of the array is the field of one element positioned at the origin multiplied by the factor array. This is function of the geometry of the array and of the phase excitation. Changing the distance and the phase of the elements, the characteristics of the factor array and of the complete field can be controlled [5],[15]. A planar array of *M x N* uniformly spaced identical microstrip antenna elements localized along the any axis of the coordinate system is considered. The pattern field of the planar array, is given by:

$$E(\theta, \phi) = F(\theta, \phi) \cdot T_x T_y \qquad (24)$$

where $F(\theta,\phi)$ is the element pattern, T_x and T_y are the factors array in the x and y directions, respectively.
The element pattern is:

$$F(\theta, \phi) = \frac{\sin\left(\frac{k_0 h}{2} \sin\theta \cos\phi\right)}{\frac{k_0 h}{2} \sin\theta \cos\phi} \frac{\sin\left(\frac{k_0 W}{2} \cos\theta\right)}{\frac{k_0 W}{2} \cos\theta} \sin\theta \qquad (25)$$

In these equations *h* is the dielectric substrate thickness and *W* is the width of the antenna element.
The factor array is calculated, considering the excitation, phase and the relative displacement between the elements as well as the dimensions and number of elements. The factor array of a rectangular planar array of *M* x *N* elements is then given by

$$T_x = \sum_{m=-N_x}^{N_x} I_{m0} \exp\left[j\left(mk_0 d_x \sin\theta\cos\phi + \beta_x\right)\right] \qquad (26)$$

$$T_y = \sum_{m=-N_y}^{N_y} I_{n0} \exp\left[j\left(nk_0 d_y \sin\theta\sin\phi + \beta_y\right)\right] \qquad (27)$$

where β_x is the phase excitation and I_{m0}, is the *real* current gain, in this x direction, β_y is the phase excitation and I_{n0}, is the *real* current gain in the y direction, and, the current in the surface is [16]:

$$I_{mn} = I_{mo} . I_{no} \qquad (28)$$

considering the phase excitation uniform, the total excitation can be defined by Imn=Io, then the array factor will be expressed as:

$$T = I_o \sum_{m=1}^{M} e^{j(m-1)(kd_x \sin\theta\cos\phi + \beta_x)} \sum_{n=1}^{N} e^{j(n-1)(kd_y \sin\theta\cos\phi + \beta_y)} \qquad (29)$$

Techniques for maximize the output power in adaptive antenna have been developed [19].

Normalizing (29), the factor array is obtained [16]:

$$T(\theta, \phi) = \left\{ \frac{1}{M} \frac{\sin\left(\frac{M}{2}\psi_x\right)}{\sin\left(\frac{\psi_x}{2}\right)} \right\} \left\{ \frac{1}{N} \frac{\sin\left(\frac{N}{2}\psi_y\right)}{\sin\left(\frac{\psi_y}{2}\right)} \right\} \qquad (30)$$

where

$$\psi_x = kd_x sin\theta \cos\phi + \beta_x \qquad (31)$$

$$\psi_y = kd_y sin\theta \cos\phi + \beta_y \qquad (32)$$

In the planar array, the element spacing and lattice must be chosen so that the total number necessary of elements in the planar array is minimized. For a rectangular lattice, the principal maximal and grating lobes can be located by

$$\sin\theta\cos\phi - \sin\theta_0\cos\phi_0 = \pm\frac{m\lambda}{d_x}, \quad m = 0,1,2,... \qquad (33)$$

$$\sin\theta\cos\phi - \sin\theta_0\cos\phi_0 = \pm\frac{n\lambda}{d_y}, \quad n = 0,1,2,... \qquad (34)$$

and the element spacing must be chosen so that

$$\frac{\lambda}{d_x} = \frac{\lambda}{d_y} = 1 + \sin\theta_m \qquad (35)$$

where θ_m is the maximal scan angle.

2.4 PBG Structures

One of the problems that emerge when we worked with photonic material is the determination of the effective dielectric constant. For being a non-homogeneous structures and that submit the incident sign at the process of multiple spread. A solution can be obtained through of numerical process called of homogenization [20].

The process is based in the theory related the diffraction of a plane electromagnetic wave incident imposed by the presence of cylinders of air immerged in a homogeneous material [17].

Chosen a Cartesian coordinates system of axes (*O, x, y, z*), shown in the Fig. 4. Consider firstly a cylinder with relative permittivity ε_1, with traverse section in the xy plane, embedded in a medium of permittivity ε_2. For this process the two-dimensional structure is sliced in layers whose thickness is equal at the cylinder diameter. In each slice is realized the homogenization process.

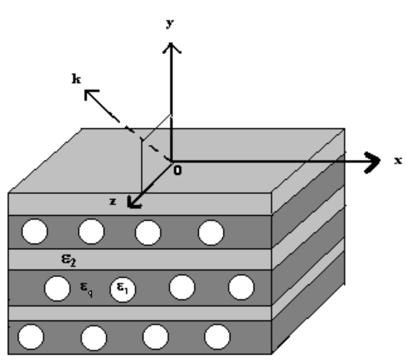


Fig. 4. Homogenized two dimensional PBG .

According to homogenization theory the effective permittivity depends on the polarization [18]. For *s* and *p* polarization, respectively, are:

$$\varepsilon_{eq} = \beta(\varepsilon_1 - \varepsilon_2) + \varepsilon_2 \qquad (36)$$

$$\frac{1}{\varepsilon_{eq}} = \frac{1}{\varepsilon_1}\left\{1 - \frac{3\beta}{A_1 + \beta - A_2\beta^{10/3} + O\left(\beta^{14/3}\right)}\right\} \qquad (37)$$

where

$$A_1 = \frac{2/\varepsilon_1 + 1/\varepsilon_2}{1/\varepsilon_1 - 1/\varepsilon_2} \qquad (38)$$

$$A_2 = \frac{\alpha\left(1/\varepsilon_1 - 1/\varepsilon_2\right)}{4/3\varepsilon_1 + 1/\varepsilon_2} \qquad (39)$$

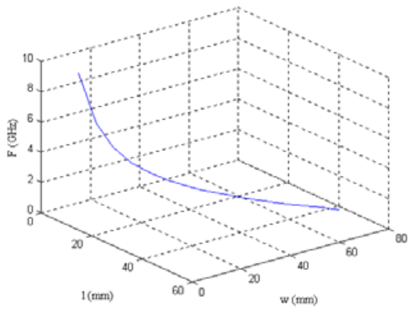
where β is defined as the ratio of the area of the cylinders over the area of the cells and α is an independent parameter whose value s equal to 0.523. The A_1 and A_2 variables in (38) and (39) were included only for simplify (37).

The process of homogenization involves a particular choosing direction, the results obtained are for small variation de incidence angle of wave vector, usually these values are between 70° and 90° degrees [18]. This concept of homogenization may well be extended to planar arrays on PBG structures. One of the most desirable features of this arrangement is the suppressing of mutual coupling of the array elements.

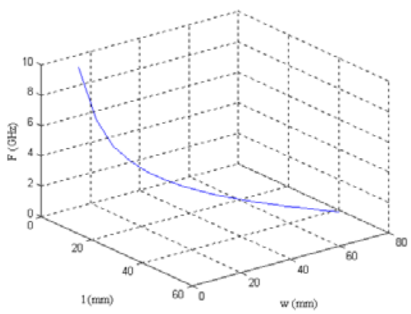
3 Numerical Results

The computational program used to calculate the resonant frequency, factor array and the radiation pattern for the phased antenna array possessing PBG material was developed in Fortran PowerStation and Matlab 6.0, using one 800 MHz PC microcomputer.

The Fig. 5 shows the real frequency of a patch antenna as function of width and length. The relative permittivity is 10.233 for s polarization and 8.7209 for p polarization. The substrate thickness is 0.7 mm.



(a)

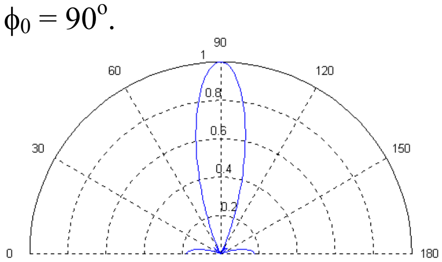


(b)

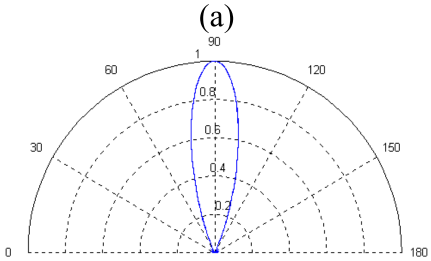
Fig. 5. Resonant frequency of microstrip patch (a) s polarization and (b) p polarization.

For the radiation patterns is considered the microstrip antenna with resonant frequency of 9.14 GHz, the width and length of patches are 10 and 5 mm, respectively, the substrate have an thickness of 0.7 mm and relative permittivity equal to 10.233 (s polarization), number of elements disposed in the x and y direction are 5 and distance between the elements radiator is $\lambda/2$, where λ is wavelength.

The Fig. 6 shows the E-plane and H-plane of microstrip antenna with the incidence angles $\theta_0 = 90^o$ and $\phi_0 = 90^o$.



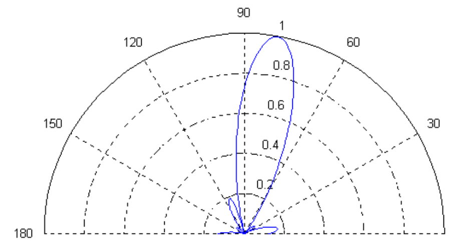
(a)



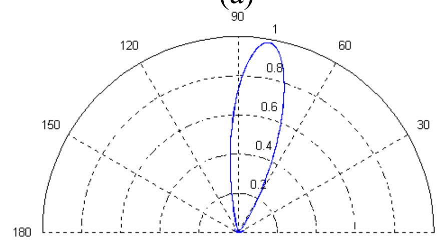
(b)

Fig. 6 Radiation patterns (a) E-Plane (b) H-Plane.

In the Fig. 7 the incident angles are $\theta_0 = 85^o$ and $\phi_0 = 80^o$. The modification in phase excitation has the objective of adjusting the antenna for new transmission or reception conditions.



(a)



(b)

Fig. 7. Radiation patterns (a) E-Plane (b) H-Plane.

Considering the parameters of structure of microstrip antenna of Fig. 2 and that the rectangular patch has the YBCO superconductor with the following parameters: $\sigma_n = 2.10^5$ S/m; $\lambda_{ef} = 150$ nm, t = 1000 nm, $T_c = 93$ K.

4 Conclusions

The Transverse Transmission Line (TTL) method was used for analysis of the microstrip phased antenna array. The inclusion of superconductor patch was made in agreement with the resistive complex boundary condition. The TTL method is an efficient and accurate method applied to the analysis and design of several planar structures. This is a very versatile method that can be used with lossless, losses, semiconductor or PBG substrate. The resonant frequency and radiation patterns were presented for the microstrip antenna array. It observed the influence of the variation of the phase excitation on the radiation pattern in the antenna array. The computational programs were developed in Fortran PowerStation and in Matlab 6.0. This work was supported by CNPq.

References

[1] Zhi-Yuan Shen, "High-Temperature Superconducting Microwave Circuits", Artech House, Inc. 1994.

[2] H. C. C Fernandes, "Attenuation And Propagation in Various Finline Structures", *International Journal of Infrared and Millimeter Waves*, Vol. 17, Nº 08, pp. 1419-1430, Aug. 1996.

[3] Humberto C. C. Fernandes, Francisco G. O. Batista, José Elesbão C. Neto, "Accurate Analysis of planar Microstrip Antenna Array", International Journal of Infrared and Milimeters Waves, vol 24, pp 1159-1169, july 2003.

[4] H.C.C. Fernandes, J. P. Silva and G.F.S. Filho, "TTL Method Applied on Microstrip Rectangular-Patch Antenna Analysis and Design", XXVIII Moscow International Conference on Antenna Theory and Technology, Moscow-Russia, Conf. Proc. pp. 424-427 Sept. 1998.

[5] Humberto C. C. Fernandes and Clenilson B. Fonseca "Phased Array with photonic material", International Microwave and Optoelectronics Conference-IMOC 2003, vol II, pp 737-740, foz do iguaçu-Brazil, Sep. 2003.

[6] Charles Kittel, "Introduction to Solid State Phisics", John Wiley & Sons, Inc., 1976.

[7] A.C.Rose-Innes and E.H.Roderick, "Introduction to Superconductivity", 2ª edition, Pergamon Press, 1978.

[8] E.A.Linton, "Superconductivity", London: Mathuen & Co. LTDA, New York: John Wiley & Sons Inc., 1964.

[9] E.B.Eckholm and S.W.McKnight, "Attenuation and Dispersion for High-Tc Superconducting Microstrip lines", IEEE MTT, vol. 38, pp. 387 - 395, 1990.

[10] D.Nghiem, J.T.Williams and D.R.Jackson, "A General Analysis of Propagation along Multiple-Layer Superconducting Stripline and Microstrip Transmission Lines", IEEE MTT, vol. 39, nº 9, pp. 1553 - 1565, Sep. 1991.

[11] J.M.Pond, C.M.Krowne and W.L.Carter, "On the Application of Complex Resistive Boudary Conditions to Model Transmission Lines Consisting of very Thin Superconductors", IEEE MTT, vol. 37, nº 1, pp. 181 - 189, Jan. 1989.

[12] Z.Cai and J.Bornemann, "Generalized Spectral-Domain Analysis for Multilayered Complex Media and High-Tc Superconductor Application", IEEE MTT, vol. 40, nº 12, pp. 2251 - 2257, Dec. 1992.

[13] K.K.Mei and G. Liang, "Eletromagnetics of Superconductors", IEEE MTT, vol. 39, nº 9, pp. 1545 - 1552, Sep. 1991.

[14] O.R.Baiocchi, R.S.Kong and T.Itoh, "Pulse Propagation in Superconducting Coplanar Striplines", IEEE trans, MTT vol. 40, nº 3, pp. 509 - 514, Mar. 1992.

[15] I.J. Bahl and P. Bhartia, "Microstrip Antennas", Artech House, Inc., 1980.

[16] C. Balanis, "Antenna Theory", Jonh Wisley & Sons, Inc., pp 487-496, 1982.

[17] Vesna Radisic, Yongxi Qian, Roberto Coccioli, and Tarsuo Itoh, "*Novel 2-D Photonic Bandgap Structure for Mictostrip Lines*", IEEE Mictowave and guided wave letters,vol. 8, No. 2 Feb 1998

[18] E. Centeno and D. Felbacq, "Rigorous vector diffraction of electromagnetic waves by bidimensional photonic crystals", J. Opt. Soc. Am. A/Vol. 17, No.2, pp.320-327, February 2000.

[19] Seungwon Choi and Dongun Yun "Design of an Adaptive Antenna Array for Tracking the Source of Maximum Power and Its Application to CDMA Mobile Communications", IEEE Trans. Antennas and Propagation, Vol. 45, No. 9, pp. 1393-1404, Sep. 1997.

[20] D. Felbacq and G. Bouchitté, "Homogenization of a set parallel fibers" , Waves Random Media 7, 245-255 (1997).