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STATE-OF-THE-ARTS RECONFIGURABLE ANTENNAS – PRINCIPLES, DEVICES, APPLICATIONS

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Abstract

The paper provides an overview of the state of the art the area of smart antennas, and is particular focused on the reconfigurable antennas as the devices the most quickly developing during in recent years. This article brings together in a review manner a comprehensive summary of high quality research contributions across basic and applied sciences. As a result a broad spectrum of topics is covered reflecting the areas in which Institute of Radioelectronics's expertise is a worldwide recognized. The transdisciplinary nature of most areas aims to stress a sense of purpose in the work developed.

Keywords: antenna arrays, reconfigurable antennas, semiconductor devices, MEMS switches, surface PIN diodes.

1. INTRODUCTION

Nowadays, the radioelectronic systems often employ the multiple antenna systems. Intelligent (smart) or adaptive antennas are the most suitable for wireless communication, especially for 3G and 4G systems. The key property of the intelligent technology is the ability to respond automatically by changing an appropriate radiation pattern. There are also numerous wireless services that operate over wide frequency range and demand different operating electrical characteristics, e.g. WLAN, Bluetooth, Wimax, automotive radars for intelligent road and others. As more wireless services are becoming more common, the available radio spectrum is decreasing. Moreover, the different countries have their own spectrum allocations. The technology that tries to overcome these problems is Cognitive Radio technology. It adds a level of computational intelligence to the system to provide the dynamic services.

Hence, it is not practical to dedicate one antenna to each service, many of these services are on at a time, while others may be required to be on all the time. In most cases, they would require automatic switching between these different modes, bands, polarizations etc. Many services means many antennas, and many standards means that more antennas are needed in conventional case of multiple antenna. In order to reduce the antenna dimensions and costs, and to improve performance characteristics, it is desirable to combine multiple functions into a single antenna system. To satisfy multi-mission functionalities, a single aperture requires an antenna array that can be quickly reconfigured to operate efficiently, e.g. at various application frequencies. The main purpose of reconfigurable aperture is to reduce the complexity of an antenna system operating on a desired frequency band, with the control over antenna gain and beam pointing direction or shape.

Reconfiguration of an antenna can be achieved through an intentional dynamic redistribution of the currents of the antenna's aperture. These changes are enabled through various mechanisms such as switching, material tuning, and structural modifications. Under this definitions, reconfiguration does not include the use of phase shifters and matching circuits that does not interact directly with the mechanism of radiation. The increased complexity is a price for enhanced performances. From a practical perspective, the additional performance provided by a reconfigurable antenna should therefore countervail the cost and complexity of reconfiguration [1].

Many solutions of the reconfigurable antennas have been described in the literature, and their practical applications have been successfully used in telecommunication systems. With the expanding demands on wireless systems one can look forward to new antenna reconfigurability specification, e.g. at multiple frequencies with varying bandwidth, polarization and radiation characteristics.

Considering all aspects of the designing process of reconfigurable antennas it can be quite demanding, but it also provides an excellent opportunity to combine state-of-the-art technologies with the antenna theory in an attempt to provide additional degrees of freedom in system performance [1].

Reconfigurable antennas come in large variety of different shapes and forms. These type of antennas are typically described by some categories, including reconfigurable radiation pattern and/or polarization and reconfigurable frequency and/or bandwidth.

There are four main mechanisms of changing the antenna's parameters:

- Mechanical/electromechanical, e.g. by using of MEMS switches,
- electronic, e.g. by using of PIN diodes,
- optical, e.g. by using of photosensitive layer,
- electrical/magnetic, e.g. by using of special substrate media such as controllable materials (ferroelectrics, liquid crystal and ferrite).

The combination of the aforementioned mechanisms is also very useful.

Considering the properties of a base design, reconfigurable antennas can be classified according to the continuity of reconfiguration, which is defined by the reconfiguration mechanism:

- continuous (reconfiguration within a range of states),
- discrete (a finite number of reconfigured states)

2. CONTINUOUSLY RECONFIGURABLE ANTENNAS

There are numerous approaches to reconfigure radiation pattern of antennas continuously.

The electronic mechanisms of changing the antenna's parameters are utilized most frequently. A frequency reconfigurable leaky wave antenna integrated with a voltage-controlled oscillator, effectively achieving an electronically controlled beam has been reported in [2]. For many applications, however, fixed or switched frequency operation would be preferable.

The next configuration of beam steering is based on an optically controlled beam steering antenna. In most of them, the signal (e.g. mm-wave) propagates along a semiconductor waveguide or in a compound dielectric waveguide containing a photosensitive layer [3]. By a specially patterned illumination, a photoinduced plasma grating is excited on the surface of the waveguide. As in a leaky-wave antenna loaded with a metal grating, in an optically controlled antenna the mm-wave signal propagating along the semiconductor waveguide interacts with the plasma grating and couples out in a specific direction which depends on the grating period. The main disadvantage of this design is that the photoinduced plasma grating also significantly attenuates EM-field and prevents the mm-wave signal from effectively propagating along the waveguide. Therefore, it is difficult to produce a radiating aperture of a reasonable size. However, a demonstration that it is possible to avoid this shortcoming has been provided in [4].

A ferrite-type dielectric waveguide antenna for phase scanning in the mm-wave region has been presented in [5]. Authors have shown a family of measured antenna patterns using the 20-slot linear array indicating high, low and intermediate beam positions for particular phase states. This data was taken at 36.25 GHz with the resultant beam positions ranging from 29^0 to 43.5^0 off broadside, a sector scan capability of nearly 15^0 . Sector as large as 24^0 have been scanned with this type of antenna by enlarging the cross-section of the ferrite rod. The price paid for this increased scanning capability are reduced gain and degraded side lobe levels. Another solution has been described in [6]. In this case the scanning sector was $\pm 20^0$, a side lobe level about –12 dB, range of control current was about ±0.7 A, power consumption – about 1 W.

The major feature of antennas which use ferroelectric dielectric materials is the change of permittivity with an applied DC bias voltage. The property of ferroelectric materials having a dielectric constant which can be modulated at high frequencies, under the effect of an electric field bias operating perpendicular to the direction of propagation of the signal, is very attractive and can be used to develop a new family of devices operating in the microwave and mm-wave range. Ferroelectric materials are in many ways dual to ferromagnetic materials. However, they have a number of advantages over magnetically controlled ferrites. In ferroelectric the driven energy required to change the property of the material is consumed primarily by the charge and is not dissipated in the ferroelectric material. Consequently less power is required to control the property of the material. Ferroelectrics also allow faster phase shifting comparing to ferromagnetic materials, they have smaller and lighter structure, and allow high power capability. Phased array approaches using ferroelectric have been presented in [7, 8]. Three possible configurations, two traveling wave types and another a lens type antenna, have been discussed. However, there is one main disadvantage: very high DC bias (max is about 13.5 kV).

A new type of reconfigurable microstrip antenna has been presented in [9]. This novel concept is based on the utilizing of voltage-controlled ferroelectric materials. The antenna consists of a multilayered structure with thin ferroelectric tape sandwiched between two dielectric slabs which are located on the conductive plate (Fig. 1).

The investigation of the microstrip antenna on ferroelectric substrates has been presented in [10]. In [11] a new method of null pattern synthesis of antenna arrays without phase shifters and attenuators has been shown there. This concept is based on utilizing voltage-controlled ferroelectric array, where the pattern of each antenna element is used to synthesize array pattern with desired nulls. It has been shown that such antenna array

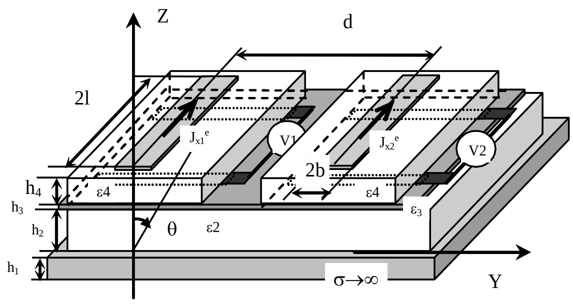

Fig. 1. Section of ferroelectric array with two elements

can provide higher directivity, narrower main lobe and lower side lobes level than conventional phased array.

The main reason why ferroelectric materials have not been used at microwave range is the large bias voltage required to change their dielectric constant and high losses of the materials.

A new low-cost scan antenna concept has been presented in [12]. The substrate of this microstrip antenna has been manufactured using a ceramic-polymer composite with modified ferroelectric powder $Ba_{0,65}Sr_{0,35}TiO_3$ and an appropriate polymer (grains of the powder were sprayed into polymer with the use of a specific method). The ceramic-polymer composite was designed to change permittivity in response to an applied electric control field for antenna utilization [13].

This ceramic-polymer composite consist of the ferroelectric powder (after being granulated according to desired size within the range 1-5μm). It has been utilized in order to obtain ceramic-polymer films. Thickness of the composite layer was selected between 100 to 500 μm. A big advantage of the ceramic-polymer ferroelectric materials over ceramic ferroelectric materials is that the former ones can have any dimensions (even $1m^2$), smaller permittivity (above 10) and high tunability comparing to the latter. It is very important for scanning antenna design. Fig. 2 shows view of the ferroelectric ceramic-polymer composite material.

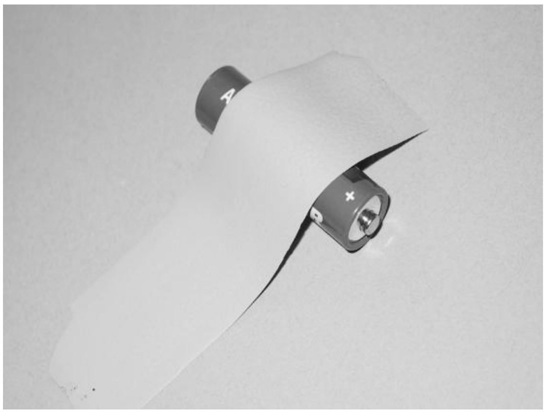

Fig. 2. Ferroelectric ceramic-polymer composite material for scanning antenna design.

Fig. 3 shows the basic configuration of the electrically controllable scanning antenna. A microstrip element which is often used is the rectangular resonator excited in the first order resonant mode. A similar field distribution is found for the first higher order mode on a microstrip line. In the first approach, this mode can be regarded as a TE_{01}-mode. As opposed to the fields in resonator the field distribution exists in a wide frequency range. For frequencies not far above the cut-off frequency, that is for $\beta / k < 1$ (β is phase constant of the first higher order mode), the fields of the first higher order mode on the microstrip line are coupled to the line very loosely resulting in a considerable radiation.

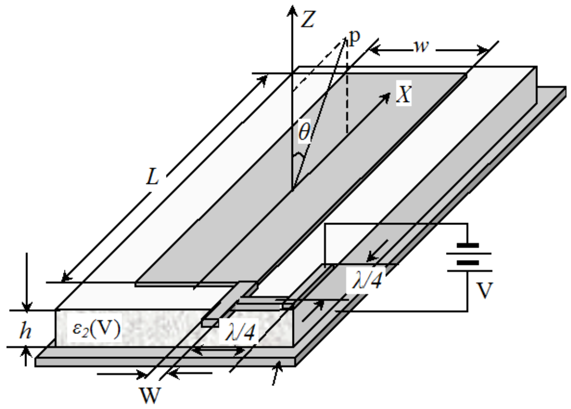

Fig. 3. Basic configuration of the electrically controllable scanning antenna

Generally the direction of the radiated beam of traveling wave antennas is given by

$$\theta_m = \sin^{-1}(\beta / k) \qquad (1)$$

where θ_m is the angle of the beam maximum measured from the broadside direction ; $k = 2\pi / \lambda$, λ is free-space wavelength. The propagation constant can be accurately evaluated by means of the rigorous analysis.

It can be seen that a 25^0 main-beam scan range has been achieved at a constant frequency f=7.9 GHz by changing the permittivity of substrate at approximately by 10%.

This is a simple, low-cost structure in which the transmission line, phase shift section and radiating aperture are contained completely within one homogeneous ferroelectric ceramic-polymer composite microstrip line with no discrete components to be assembled for aperture integration. Presented antenna has been designed and tested in frequency region 7.7÷7.9 GHz. The antenna (which width is equal *w*) is fed asymmetrically with a narrow quasi-TEM line (which width is equal W). Wider microstrip transmission line (acting on the first higher order mode) operating as antenna is printed on 200 μm ceramic-polymer ferroelectric substrate and has a width of 10.5 mm. The length *L* of the strip has been chosen to be equal to 96 mm. The bias of the substrate is achieved using special DC-block. In [12] has been shown that the beam angle can easily change over 30^0 with varying DC bias field up to 200V.

Beside the ferrite and ferroelectric materials liquid crystals show very good RF performance. In [14] a novel approaches of tunable devices for millimetre wave applications based on liquid crystal have been presented. Authors have described a concept of a tunable liquid crystal phase shifter in LTCC (Low Temperature Cofire Ceramics) technology and a tunable high-gain antenna based on a liquid crystal tunable reflectarray. It has been shown that continuously beam scanning is between $\pm 25^0$. Other example of using of a liquid crystal can be found in [17]. Authors have proposed the use of a liquid crystal substrate for a patch antenna whose frequency can be tuned by changing the biasing voltage across the substrate. It has been found that by varying the biasing voltage from 0 V through 11V, the operating frequency of the circular patch antenna can be changed from 1.08 GHz up to 2.35 GHz.

3. DISCRETELY RECONFIGURABLE ANTENNAS

Another approach to reconfigure characteristics of antennas with finite number of reconfigured states is the use of RF switches.

The fundamental role of a switch or relay is a device to make or break an electric circuit. In static and quasi-static regimes, a switch operates simply as either a conduction path or a break in the conduction path. However, switch operation in an RF system will include additional electrical properties. Switch resistance, capacitance and inductance along the RF signal path must be taken into account in the analysis of the system. In RF antenna systems, switch function typically entails controlling and directing the flow of RF energy along a desired RF path. Traditionally, this path may include any of the RF subsystems leading to the antenna feed distribution network as well as the antenna feed and, in the case of arrays, any power distribution network. Irrespectively of the type of switch used, there are several important characteristics that must be evaluated for all RF switch applications and particularly reconfigurable antenna designs. The selection of switch type depends fundamentally on the switching speed required by the application and the switched signal power level. Other critical parameters to consider in the selection of RF switches include impedance characteristics, switch biasing and activations conditions, package and form factor, and switch cost.

Generally, reconfigurable antennas by RF switches technology can be divided into two groups:

- Ones which use fixed separated switches placed on the aperture (as switches the following can be used: PIN diodes, FET transistors or MEMS),
- Ones which use temporarily created switches, e.g. made on a semiconductor substrate.

An example of the first group is a reconfigurable aperture concept derived from the fragmented aperture design where the configuration of the fragmented aperture may be switched by the user to obtain different functionalities [16]. These reconfigurable apertures are derived from the new class of antenna, which consists of a matrix of conducting patches with switches between some or all of the patches. These reconfigurable apertures can change functionality by opening or closing different connections between these patches.

An example of the second group is a structure presented in [17], in which the plasma regions of fairly high electrical conductivity are temporarily created on a silicon substrate. These regions define the antenna structure, and they can be changed to create different antennas. The key element of the antenna is a semiconductor chip that contains a set of individually controlled PIN structures. Electromagnetic waves propagate through the chip, which also serves as a planar dielectric waveguide. The PIN structures locally affect the wave propagation velocity and the antenna can form a beam in practically any direction within a wide steering angle.

In this part of the paper the results of design and investigation of some semiconductor antennas of the second group have shown. The semiconductor antenna means that antenna utilizes the semiconductor material as a substrate, which parameters can be varied.

The first antenna to be discussed is a new fixed-frequency beam-steerable reconfigurable leaky-wave antenna [18]. The concept is based on the usage of a semiconductor substrate for creating surface p-i-n devices SPIN [19] which are utilized to switch between the different aperture configurations by means of width of aperture.

It has been observed that a change of the width of the microstrip line operating in its first higher-order mode is accompanied by a noticeable shift in the cutoff frequency of the first higher-order mode. This effect has been used in the design of antennas with a continuously adjusting operating frequency range. It can be seen that an approximately 35^0 main-beam scan range has been achieved at a constant frequency f=7.9 GHz by lightly changing the width of the aperture.

Application of the semiconductor substrate allows to create surface p-i-n devices which can be utilized to switch the width of the aperture as in the case of antennas with a reconfigurable aperture (Fig. 4).

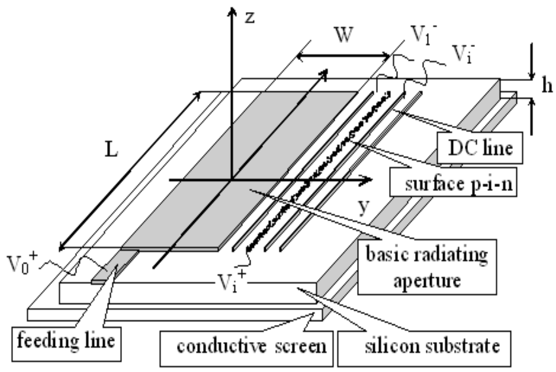

Fig. 4. Reconfigurable leaky-wave antenna concept

The second example of reconfigurable antenna is more advanced structure based on the array of surface p-i-n diodes integrated with radiators. “Generating” a desired radiation pattern can be obtained by the following steps (Fig. 5): the traveling wave propagates along the semiconductor (silicon) layer, on which the grid of SPIN devices is formed. In the SPIN diodes, the carriers are confined to the top surface. Injection of a DC current into SPIN diodes induces plasma of carriers in the intrinsic region, which appears to be like a conductive layer for microwaves. This diode array is addressable by a control circuit.

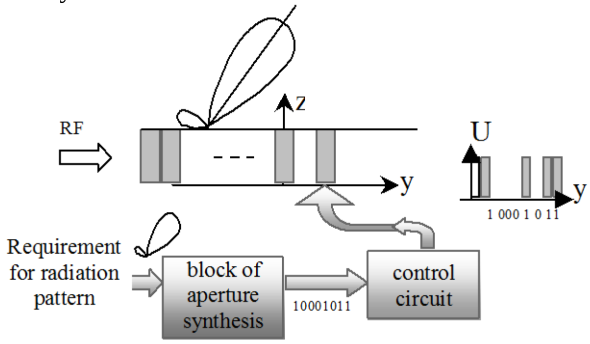

Fig. 5. Concept of the reconfigurable antenna with the grid of SPIN diodes

In our case, at the first moment, the grid of SPIN diodes is turned OFF (no bias). In this state, the highly resistive silicon substrate behaves like insulator and may be used as a dielectric waveguide. Then a block of the synthesis of the requested radiation pattern processes the initial data. It outputs as a result, a binary sequence that defines, which of SPIN devices should be turned-on is obtained. The number of bits at bit sequence depends on the number of SPIN diodes. In our cases, we have investigated 64 and 128 pairs of the SPIN diodes.

The sequence is passed to a control circuit, in order to obtain a requested DC current for activating the SPIN diodes. Thereby a conductive aperture pattern is created, which in turn causes the generation of the desired shape of radiation pattern. Thus, by turning the SPIN structures ON and OFF selectively, it is possible to obtain instantaneously the desired conductive pattern. Therefore, at a fixed frequency, the main beam can be electronically switched among the several shapes of the radiation pattern or beam directions, or the antenna may be tuned to several desired frequencies.

For the purpose of a practical implementation, it was assumed that switching-ON an individual SPIN is represented as “1” and turning it OFF as “0”.

Using of reconfigurable antennas is advantageous for many applications. First of all, the reconfigurable antennas can be used for obtaining broadside beams for different frequencies. It has been proved that for a standard equidistance array excited by a traveling wave, it is impossible to obtain broadside radiation covering range from 20-40 GHz, while our design reconfigurable aperture makes such coverage possible.

Another application is the use of a reconfigurable antenna to design a scanning antenna array. Our results prove that the desired directions in the range of $\pm 40^0$ can be easily covered. Additional advantage is the lack of diffraction beams for a large scanning. These diffraction beams are a great disadvantage of the phased array antennas.

The key element of the presented concept is a surface PIN (SPIN) device. SPIN devices are not widely used in the microwave and millimeter wave range applications. The structure of the SPIN diode differs significantly from a conventional PIN diode used as a switching device and well known to microwave engineers. The structure of a standard PIN diode is bulky, even if the device is fabricated in a planar technology. The inner intrinsic (very lightly doped) layer is placed between two areas with high concentration of carriers - N+ and P+. Dimensions of this inner area depend on, for example, the desired isolation, switching time, and required breakdown voltage. In some cases the structure is cylindrical. It provides requested mechanical, thermal and electrical parameters of the devices.

In the OFF state, while the diode is not biased, the SPIN device offers the high resistance of the area between the doped regions. In the ON state, it is characterized by the low resistance of the plasma of injected carriers in the surface area, when the diode is strongly biased in the forward direction. At the forward bias a wide slot (between two conductive area) in metallization is short-circuited by conducting plasma of carriers.

The plasma should be conductive enough to become an equivalent of a quasi-metallic layer. It is also requested, for several applications, that the metal contacts, used for biasing the diode, should be as small as possible. In order to be used at microwave and millimeter wave ranges, the SPIN diode has to provide a possibility of the dynamic switching between OFF and ON states.

A concept of a reconfigurable antenna device has been based on a reconfigurable slot aperture, which was placed instead of one wall of a metallic rectangular waveguide [20]. A standard rectangular waveguide WR-42 has been used with SPIN diodes mounted at the narrow wall of the waveguide.

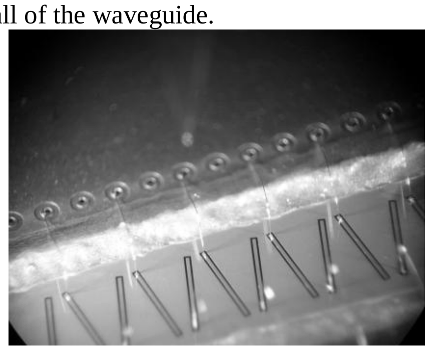

Fig. 6. Part of the ready device wired to the control system

The SPINs forming array of „slots” are placed in a skew-symmetric manner, which is clearly visible in Fig. 6 showing a fragment of this chip wired to the external system. The reconfigurable elements form an array similar to a waveguide slot antenna but with large amount of slots. The distance between the nearest slots on the aperture has been chosen as small as possible.

Every slot could be used for generation of a requested radiation pattern.

This antenna has been investigated in the wide frequency range: from 17 GHz to 34 GHz for different configurations of the diodes being in the ON and OFF states. The results, published in [21], prove that this device can emit radiation beam to the desired direction or it can operate at different frequencies, while supporting radiation in the similar directions.

CONCLUSIONS

The paper presents the results of the investigation of reconfigurable antennas. Discussed solutions have been based on the ferroelectric and semiconductor materials. Such approach allows us to design the electronically controlled beam-steering and electronically reconfigurabled antennas. The possibility of the reconfiguration of the antenna aperture is very promising. The key element of the reconfigurable antenna is a surface PIN (SPIN) diode whose conductivity changes proportionally to the plasma density. SPIN structures can be activated selectively and cause, in turn, a generation of the desired shapes of radiation pattern.

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