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TIME-DOMAIN MODELING OF SHORT PULSES RADIATION WITH APERTURE DECOMPOSITION METHOD

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This paper is dealt with a general modeling method for Time Domain analysis of aperture antenna pulse radiation. Non-synchronous excitation is the main feature of the proposed approach. We solve in a closed-form the problem of pulse radiation from the rectangular aperture with uniform amplitude distribution and linear time delay distribution (it corresponds to excitation with travelling wave). Then we use a decomposition approach to calculate pulse fields radiated by Tapered Slot Antenna. We decompose an aperture of TSA into elementary rectangular apertures with given amplitudes (taking into account wave impedance and the fact that the power exponentially decays due to radiation losses) and excitation delays. The radiated field can be obtained by totalizing the fields from each elementary aperture. Then we calculate the fields from an array of TSA in H- and E-plane. We set time delay for each antenna in the array to have the ability of steering the radiation pattern of such system. Some radiation patterns for a single TSA as well as for arrays of TSA with different time delay distribution are presented. Some physical interpretations of the obtained results are given as well.

Introduction

In light of constantly increasing interest to impulse radiating antennas for radar, GPR, secret communication, and so on we need good steerable radiating systems with high directivity and capable of radiating ultra short pulses. In this paper we give some exploration of a time array (Time Domain analog of phased array) with a Tapered Slot Antenna as a basic element.

Time arrays (i.e. arrays with the ability to set the excitation time delay for each element separately) allow to steer the beam in far zone and to perform 3D scanning in near zone as well. This latter focusing feature may be very useful in GPR applications.

We use a TSA as a basic element of the array since it was shown [1] that end-fire antennas (such as TSA) have some advantages in directivity over broadside antennas (such as horn, reflector) for short pulse radiation case.

We introduce a very simple and straightforward decomposition scheme to model pulse radiation of any aperture antenna. We use this approach to calculate transient field radiated by TSA [2]. Though this type of UWB antennas is known since 1979 it has been closely investigated only in Frequency Domain [3-7].

Pulse Radiation of an Aperture

In many cases pulse antenna can be adequately described by current distribution on the aperture. Let us consider an aperture with arbitrary current amplitude and time delay distribution and arbitrary exciting pulse shape. The field in the far zone can be obtained as follows [8] (notations are explained in Fig. 1):

$$\boldsymbol{E}(\boldsymbol{R},t) = -\frac{\mu_0}{4\pi R_0}[[\boldsymbol{e}_0 \times \boldsymbol{n}] \times \boldsymbol{n}] \times$$
$$\iint_S A_j(\xi,\eta)\frac{\partial}{\partial t} f\left(\tau - t_d(\xi,\eta) + \frac{x\xi+y\eta}{cR_0}\right) d\eta d\xi\ , \quad (1)$$

where $A_j(\xi,\eta)$ is the amplitude distribution; $f(t)$

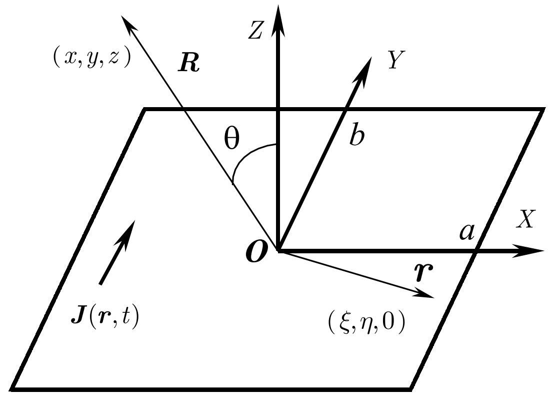

Fig. 1. *Problem geometry*

is the exciting pulse; $t_d(\xi,\eta)$ is the time delay distribution; $(\xi,\eta,0)$ is a point on the aperture; $\boldsymbol{e}_0$ is the current unit vector (it determines polarization); $\boldsymbol{R}=(x,y,z)$ is the vector to a point of observation; $\boldsymbol{n}=\boldsymbol{R}/|\boldsymbol{R}|$; $\tau=t-R_0/c$ is the retarded time. This is a general formula for aperture radiation analysis (in far zone) which takes into account non-synchronous excitation.

Decomposition. Basic Solution

Formula (1) yields a simple closed-form solution for the case of rectangular aperture ($2a\times 2b$) with uniform amplitude distribution and linear time delay distribution (in H-plane):

$$E(R_0,t,\theta)=-\frac{\mu_0}{4\pi R_0}\frac{2bc}{\sin\theta-\alpha}\times$$
$$\left\{f\left(\tau+(\sin\theta-\alpha)\frac{a}{c}\right)-f\left(\tau-(\sin\theta-\alpha)\frac{a}{c}\right)\right\},\quad(2)$$

where $\alpha=c/v$, v — the signal propagation velocity along Ox.

Now we can use this solution to calculate the fields of any aperture, if only this aperture is represented as a number of rectangles with the given uniform amplitudes and the given linear delay distribution. We just need to decompose the aperture in the above mentioned way, apply formula (2) to each rectangle and totalize the fields from all the decomposition elements. Let us apply this approach to analysis of Tapered Slot Antenna.

Tapered Slot Antenna Analysis

Tapered Slot Antenna with decomposed aperture is shown in Fig. 2. We assume that the exciting pulse travels along the antenna with the speed of light, i.e. $\alpha=1$ in formula (2). Besides, when determining the amplitudes of each section we suppose that the power in this transmission line decreases exponentially due to radiation losses:

$$ZI^2=P=\text{const}\cdot e^{-2\beta x},\quad I\approx\frac{e^{-\beta x}}{\sqrt{Z(x)}},\quad(3)$$

$Z(x)$ is the wave impedance in the tapered slot line, we use formulas from [3] to calculate it. The current distribution in cross-section takes into account singularities on the metal edges [4-6]. We neglect multiple reflection in the line in this consideration mainly due to the fact that the signal fades out significantly to the end of sufficiently long antenna.

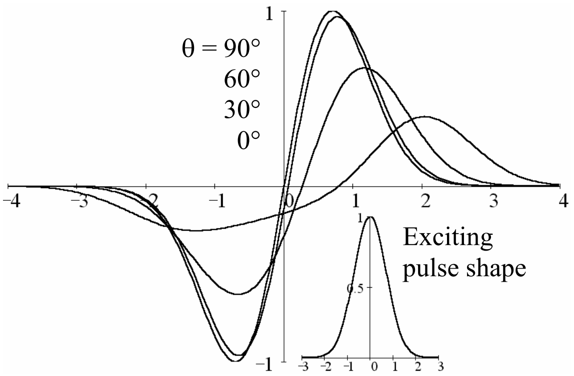

Fig. 3. *Time shape of radiated field in far zone*

The antenna under consideration has the following parameters: linearly tapered form with tapering angle 20°; exciting pulse is of Gaussian form: $f(t)=\exp\left(-\left(\frac{t}{T}\right)^2\right)$; antenna length is $L=4cT$; substrate: $\varepsilon=2.22$, $d=0.017\,cT$.

In Fig. 3 one can see the calculated time shape of radiated in different directions fields. The first derivative of the exciting pulse is radiated in the endfire direction (it follows from (2), where finite differ-

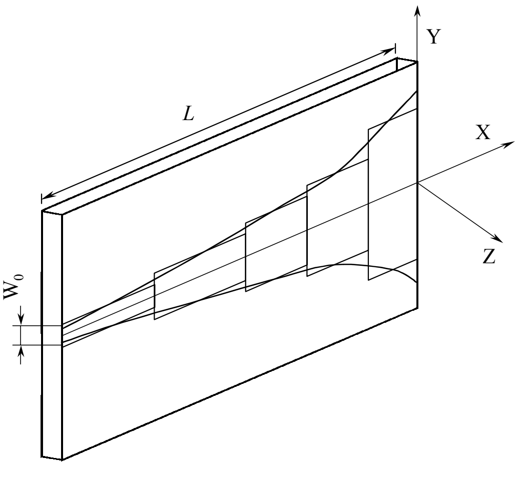

Fig. 2. *Tapered Slot Antenna*

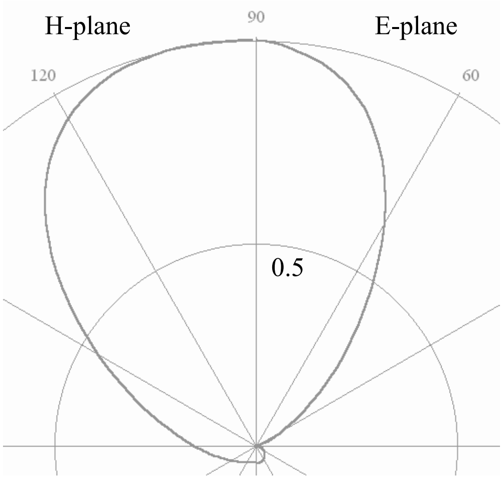

Fig. 4. *Peak power radiation pattern of the TSA*

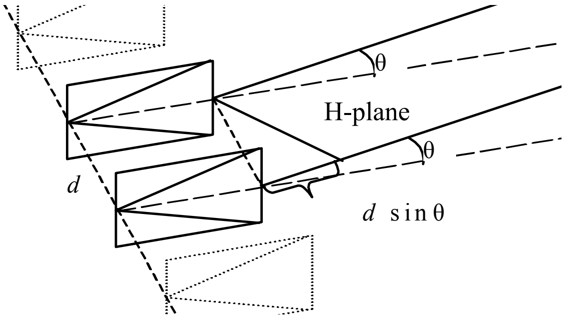

Fig. 5. *Geometry of the array.*

ence turns into derivative for $\theta = 90°$), while the time form of the field radiated in side direction is a sum of two unequal pulses that come from the beginning and from the end of the antenna.

Radiation patterns calculated for peak power:

$$W(\theta) = \max_{-\infty<t<\infty} E^2(t,\theta) \qquad (4)$$

are presented in Fig. 4.

Arrays of TSA

Let us consider now time arrays of TSA. As was mentioned in the introduction, time arrays posses the ability of steering the beam in far zone by setting certain time delays for each element of an array. The array of TSA arranged in H-plane is shown in Fig. 5.

The field radiated by such a system can be obtained by summing the fields from each element with taking into account time delays resulting from differences in propagation time $d\sin\theta / c$ (see Fig. 5) and different excitation time τ_{set}:

$$E_{sum}(t,\theta) = \sum_{i=1}^{N} E\left(t + \left(i - \frac{N+1}{2}\right)\left(\frac{d\sin(\theta)}{c} + \tau_{set}\right), \theta\right). \quad (5)$$

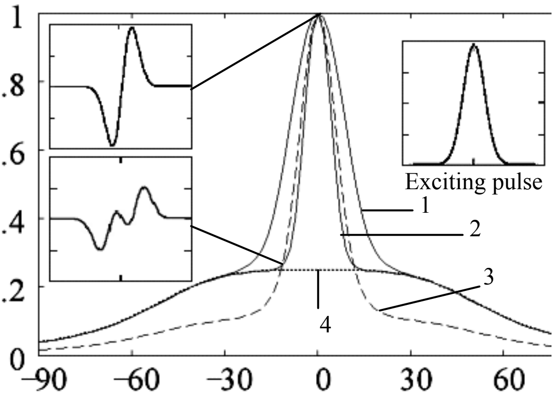

Fig. 6. *Peak power radiation patterns for:*
1 – $N = 2$, $d = 4\ cT$ **2** – $N = 2$, $d = 8\ cT$
3 – $N = 3$, $d = 4\ cT$ **4** – $N = 1$

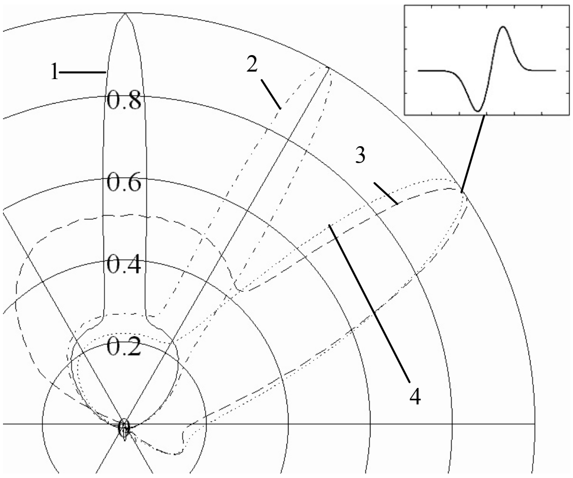

Fig. 7. *Patterns for different deviation angles:*
1 – $N = 2$, $d = 8\ cT$, $\theta_{dev} = 0°$; **2** – $N = 2$, $d = 8\ cT$, $\theta_{dev} = 30°$
3 – $N = 2$, $d = 8\ cT$, $\theta_{dev} = 60°$; **4** – $N = 3$, $d = 4\ cT$, $\theta_{dev} = 60°$

We investigate elements arrangement effect on the peak power radiation pattern. To this end we plot in Fig. 6 some radiation patterns for different number of elements *N* and different spacing *d*. We adduce the pattern for the single element (divided by N^2) to show that after separating the pulses from individual elements the array pattern corresponds exactly to the pattern of 1 element. It is explained in the inset with time form at the border of main lobe. One can conclude from this figure that the beamwidth is defined by the distance between outermost elements, whereas main-lobe to sideway radiation ratio is defined by the number of elements.

In contrast to phased arrays we haven't any side lobes for time arrays, so we needn't have a dense array elements arrangement. Moreover, sparse aperiodic arrangement is more desirable. Indeed, while an array radiates one pulse in main direction, it radiates pulse train outside of main lobe. This pulse train has a significant power spectral density at the repetition frequency (dependent on the angle) and its harmonics and can interfere with narrowband receivers. Moreover, aperiodic arrangement leads to reduction of ringing resulting from multiple reflections between TSA in the array, because this reflections will be unsynchronized.

And at the end of our consideration we plot in Fig. 7 some radiation patterns illustrating beam steering. Note that when the deviation angle is out of the single element main lobe, the array radiation is ineffective.

Conclusions

We introduce the decomposition technique for calculating the pulse field of aperture antennas. Time domain analysis of TSA was performed with this technique. Time array of TSA was considered as well. It was shown that to avoid interference with narrowband receivers one should use aperiodic sparse elements arrangement in the array.

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МОДЕЛИРОВАНИЕ ВО ВРЕМЕННОЙ ОБЛАСТИ ИЗЛУЧЕНИЯ КОРОТКИХ ИМПУЛЬСОВ МЕТОДОМ ДЕКОМПОЗИЦИИ АПЕРТУРЫ

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В статье описан общий метод моделирования во временной области импульсного излучения апертурных антенн. В аналитическом виде решена задача излучения импульса прямоугольной апертурой с однородным амплитудным распределением и линейным распределением задержки возбуждения (что соответствует возбуждению бегущей волной). Решение было применено для вычисления импульсного поля, излучаемого расширяющейся щелевой антенной (РЩА), с использованием декомпозиционного подхода. Апертура РЩА представляется в виде набора элементарных прямоугольных апертур с заданными задержками возбуждения и амплитудами (определенными с учетом волнового сопротивления линии и экспоненциального затухания мощности в линии, обусловленного потерями на излучение). Излученное поле можно получить как сумму полей от этих элементарных апертур. Затем мы рассчитали излучение от решетки РЩА в Н- и Е-плоскостях. Временная задержка возбуждения может быть установлена для каждого элемента массива – это дает возможность управлять диаграммой направленности подобной системы. Представлены результаты расчетов диаграмм направленности как для отдельной РЩА, так и для решетки РЩА с различными распределениями задержек возбуждения. Дано физическое объяснение полученных результатов и рекомендации по вопросам электромагнитной совместимости подобных антенных решеток.

МОДЕЛЮВАННЯ У ЧАСОВІЙ ОБЛАСТІ ВИПРОМІНЮВАННЯ КОРОТКИХ ІМПУЛЬСІВ МЕТОДОМ ДЕКОМПОЗИЦІЇ АПЕРТУРИ

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У статті описано загальний метод моделювання у часовій області імпульсного випромінювання апертурних антен. В аналітичному вигляді розв'язано задачу випромінювання імпульсу прямокутною апертурою з однорідним амплітудним розподілом та з лінійним розподілом затримки збудження (що відповідає збудженню біжучою хвилею). Розв'язок було використано для обчислення (декомпозиційним методом) імпульсного поля, яке випромінюється щілинною антеною, що розширюється (ЩАР). Апертура ЩАР розбивається на елементарні прямокутні апертури із заданими затримками збудження та амплітудами, які визначаються з урахуванням хвилевого опору лінії та експоненціального згасання потужності хвилі у лінії, зумовленого втратами на випромінювання. Випромінене поле можна отримати як суму полів від цих елементарних апертур. Далі було обчислено випромінювання від решітки ЩАР у Н- та Е- площинах. Часова затримка збудження може бути встановлена для кожного елемента – це надає можливість керувати діаграмою спрямованості такої системи. Представлено результати обчислення діаграм спрямованості як для окремої ЩАР, так і для решітки ЩАР із різними розподілами затримок збудження. Дано фізичне пояснення отриманих результатів та рекомендації щодо електромагнітної сумісності таких антенних решіток.