Spatially Modulated Metamaterial Array for Transmit (SMMArT)

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Abstract**—Borrowing from slow-light optics, a metamaterial-based transmit array is conceived that employs a low-group-velocity serial feed line. This feed configuration facilitates a new manner of physical implementation for fast-time spatial modulation of a radar waveform based on the development of a serial-fed slotted Clarricoats-Waldron waveguide, thus realizing a physical MIMO radar implementation that avoids the need for phase-shifters and requires only a single waveform generator. The theory and principles of operation for SMMArT are presented, as well as the electromagnetic design principles for the low-group-velocity waveguide structure. High-power and planar array manifestations are also discussed.**

I. Introduction

Continued advances in radar necessitate joint consideration of the physical electromagnetic interface, RF systems engineering, and signal processing [1]. Sophisticated electromagnetic design is necessary, for instance, to address some of the practical aspects of MIMO radar [2-5]. Within this joint context, we consider fast-time spatial modulation [6-8], which represents a form of MIMO radar that is a generalization of the frequency-diverse array [9-11]. Specifically, this realization of spatial modulation is examined from the perspective of a novel metamaterial-based slotted waveguide array that permits joint consideration of the array and waveform structures so as to facilitate greater exploitation of the available design degrees of freedom.

The past two decades have witnessed the emergence of the field of metamaterials, which has opened the door to a host of new applications across the electromagnetic spectrum from RF [12] to optics [13]. Such 'engineered materials' are well suited to address the notion of holistic radar design whereby the radar operation and constituent components are conceived as a whole [1,14,15], in much the same manner as the far superior sensing capabilities found in nature [16]. Within this holistic context we introduce the concept of a Spatially Modulated Metamaterial Array for Transmit (SMMArT) as a physical MIMO radar formulation conceived to provide a waveform-dependent radiation pattern that is amenable to the high transmit power of typical radar applications.

II. SMMArT Feed Configuration

In Electronically Scanned Arrays (ESAs) [17] each radiating element is connected to the feed line by means of a phase-shifter. Common architectures for arrays of passive antennas are the constrained series and parallel (or corporate) feeding systems, in which power is supplied by a single high-power oscillator/amplifier to each radiating element [18]. The beam is typically scanned by coherently altering the phase of the individual radiating elements through local phase-shifters. Leaky-wave slot antennas [19] and Frequency Scanned Arrays (FSA) [20] in the constrained series feed configuration exploit a frequency dependent phase shift of the electromagnetic mode propagating along the feed line.

The SMMArT architecture is a metamaterial-based array for the specific purpose of realizing fast-time spatial modulation. Here beam-steering is achieved by an appropriate phase modulation of a single excitation waveform without relying on individual phase-shifters at the radiating elements or the need to generate multiple different waveforms (via arbitrary waveform generators (AWG) or direct digital synthesizers (DDS)). SMMArT is based on a constrained series traveling-wave (non-resonant) feed architecture, as schematically illustrated in Fig. 1. SMMArT departs from conventional frequency-scanned leaky-wave antennas [19] in terms of beam-steering mechanism in that it relies on a slow-group-velocity transmission line in order to perform intra-pulse and inter-pulse radiation-pattern modulation.

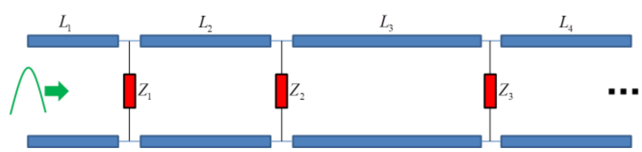

Fig. 1. Schematic of a serially-fed array of antennas represented by their imput impedances Z_i.

Figure 1 illustrates an idealized model for SMMArT in which the shunt impedences distributed along the transmission line are the radiation resistances of a set of identical isotropic radiators located at the Cartesian positions $\boldsymbol{r}_n=(0,0,z_n)$. The current density over the radiating elements can be written as

$$J(z,t)=\sum_n I_n(t)\delta(z-z_n)\,. \tag{1}$$

We assume a voltage waveform at the generator defined as

$$V(t)=V_0(t)e^{-j\varphi(t)}\,, \tag{2}$$

with amplitude $V_0(t)$ and phase $\varphi(t)$. The amplitudes $I_n(t)$ from (1) are related to the input voltage waveform (2) as

$$I_n(t)=\frac{1}{Z_n}V_0\left(t-\frac{z_n}{v_g}\right)e^{-j\varphi\left(t-\frac{z_n}{v_p}\right)}\,, \tag{3}$$

where v_g and v_p are the group velocity and the phase velocity, respectively. The radiated far-field in spherical coordinates can be obtained from Jefimenko's equations [21] applied to (1) and (3), yielding

$$E(r,\theta,t) = \frac{1}{r}\sum_{n=1}^{N}\frac{1}{Z_n}V_0\left[\left(t - \frac{r}{c}\right) - \frac{z_n}{v_g}\right] e^{\phi\left[t - \frac{r}{c}\left(1 - \frac{z_n\cos\theta}{r}\right) - \frac{z_n}{v_p}\right]} . \quad (4)$$

While (4) is applicable to any serially-fed array, the distinctive feature of SMMArT is a low-group-velocity transmission line such that $v_g << c$.

The low-group-velocity transmission line employed in SMMArT serves the purpose of compressing the *spatial* extent along the transmission line of the waveform feeding the radiating elements. Neglecting group velocity dispersion effects, the spatial extent of a pulse of duration τ propagating on a transmission line is approximately equal to $d = v_g\tau$. For a transmission line operating in the fundamental TEM mode in air in which $v_g \approx c$, a pulse of temporal duration τ = 100 μs would have a spatial extent of d = 30 km, far exceeding the dimensions of any practical array. As a result, essentially the same portion of the waveform would encounter all the radiating elements simultaneously and the beam position would be static as a function of fast time, with the direction determined by the feed system delays alone.

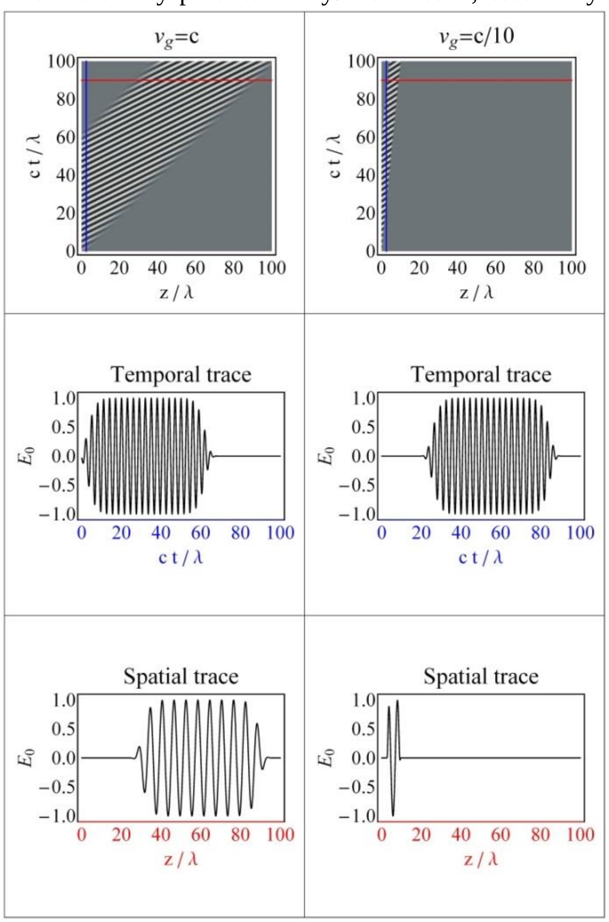

Fig. 2. Spatial and temporal distribution of a pulse in a waveguide with high group velocity v_g=*c* (left column) and in a waveguide with low group velocity v_g=*c*/10 (right column). All distances are normalized with respect to the vacuum wavelength λ. The temporal traces are evaluated over the blue lines, and the spatial traces are evaluated over the red lines in the top row.

However a low group-velocity ($v_g << c$) feed-line would make the pulse much shorter spatially. This concept is illustrated in Fig. 2, which provides a comparison of the spatial and temporal extent of a pulse propagating in a transmission line with high and low group-velocity. As apparent from the spatial traces (bottom row) in Fig. 2, the spatial extent of the waveform is significantly compressed for the lower group velocity. The salient attribute for a spatially-modulated MIMO radar emission is that for a low group-velocity waveguide different portions of the waveform encounter the radiating elements at a given time, thereby allowing for emission design to be accomplished through joint design of the waveform and the serial feed system.

III. Slow Group Velocity Waveguide

Now consider the physical realization of the low group velocity feed line discussed above. Group velocity [22] offers an accurate description of the energy velocity associated with narrow-bandwidth signals in many electromagnetic systems of interest such as waveguides and transparent extended media (with some important exceptions [23] related to the presence of absorption or gain bands in the spectral region of interest for the medium in which the field propagates). The group velocity is sub-luminal ($v_g \le c$) in every instance that is descriptive of the rate of energy transport, and such is the case in microwave waveguides and transmission lines. While phase velocity plays a critical role in the radiation properties of a guided-wave system, in general it is not directly related to energy transport and therefore its value is not bound by the speed of light in vacuum. Both the group and the phase velocity are essential in the determining the radiation properties of leaky wave antennas and serially fed arrays under pulsed excitation.

Here we are concerned with the radiation from guided-wave systems operating with low group-velocity ($v_g << c$). This operating regime can be accessed in a variety of systems. Perhaps the simplest example is a single-mode hollow metallic waveguide excited at a frequency f near cut-off frequency f_c. Group and phase velocity are given in this case [24] by

$$\begin{aligned} v_g &= c\left(1 - f_c^2 / f^2\right)^{1/2} \\ v_p &= c / \left(1 - f_c^2 / f^2\right)^{1/2} \end{aligned} . \quad (5)$$

As evident from (5), as the group velocity approaches zero the phase velocity diverges, leading to a nearly constant phase in the propagation direction and making it nearly impossible to control the modal phase along the waveguide. Slow group velocity can be obtained also in periodically loaded structures exhibiting an electromagnetic band-gap [24], but due to the longitudinal periodicity a unique phase velocity cannot be properly defined. In both cases just described, controlling the phase of the electromagnetic field in the low group velocity regime is impractical.

Here we address the issues discussed above by proposing an antenna architecture based on a waveguide structure supporting low-group velocity modes with finite and well-defined phase velocity. This system relies on a slotted waveguide of the Clarricoats-Waldron type [25,26]. The Clarricoats-Waldron waveguide features two essential elements: *a*) a hollow metallic waveguide that is *b*) coaxially loaded with a high permittivity rod. An example layout for X-band operation is shown in Fig. 3.

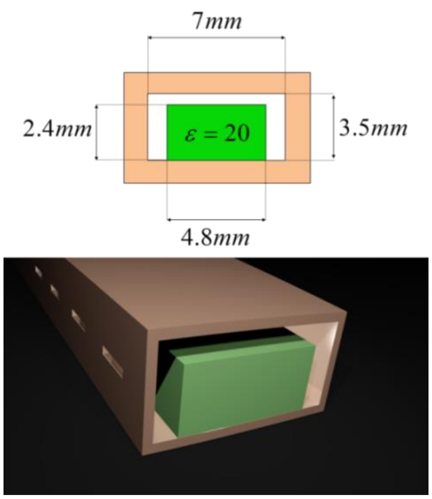

Fig. 3. Layout of a slotted rectangular Clarricoats-Waldron waveguide for operation around 10GHz.

This inhomogeneous waveguide system is quite unique in that it supports backward modes (i.e. with antiparallel phase and group velocity), in spite of the fact that the structure is uniform in the propagation direction. The conditions of existence of such backward-wave modes are related to band-repulsion effects in correspondence with an accidental degeneracy of the first two modes supported by the structure [27]. The dispersion relation associated with the structure of Fig. 3, which is designed to operate around 10GHz, is shown in Fig. 4. The negative slope of the branch of dispersion curve (shown in red) is indicative of a backward-wave mode. The blue branch on the other hand indicates a forward-wave mode. Notice that for frequencies in the 10GHz - 11GHz interval, two degenerate forward-wave and backward-wave modes are allowed. Interestingly, around 10GHz, where the two branches

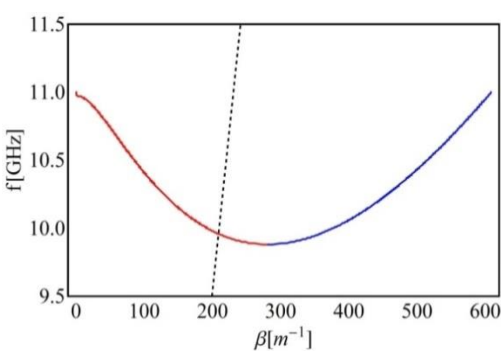

Fig. 4. Dispersion relation for a Clarricoats-Waldron waveguide. The red branch and the blue branch indicate the backward-wave and forward-wave modes, respectively. In the frequency range from 10GHz to 11GHz the two modes coexist, while for frequencies above 11GHz only the forward-wave mode is supported. The dashed black line indicates the light-line.

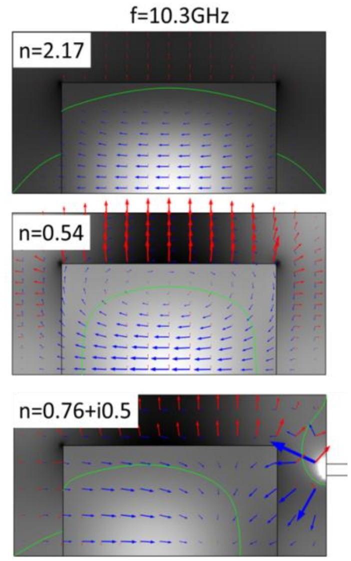

Fig. 5. Modal field distribution and effective indices of the forward-wave mode (top) and of the backward-wave mode (bottom). The red and blue arrows indicate the electric and the magnetic fields, respectively. The green line denotes the region of zero Poynting vector.

coalesce, the dispersion curve flattens out indicating a vanishing group velocity.

Physical insight about the operation of the Clarricoats-Waldron waveguide may be gained by analyzing in detail the field distributions leading to the anomalous behavior of this structure. Due to the dielectric discontinuity within the guide, the supported modes are necessarily hybrid. In particular, the fundamental mode is a mixture of the TE10 and TM11 modes of a rectangular metallic waveguide [24]. The electric and magnetic field distributions of the fundamental backward mode at 10 GHz are shown in Fig. 5. Interestingly enough, the electric field is reminiscent of the TE10 mode, while the magnetic field retains the symmetry of the TM11 mode. The reversal of the magnetic lines of force around the two convective regions visible in the top two panels of Fig. 5 causes the Poynting vector to change sign and become negative for positions external to the green line shown in Fig. 5, where the

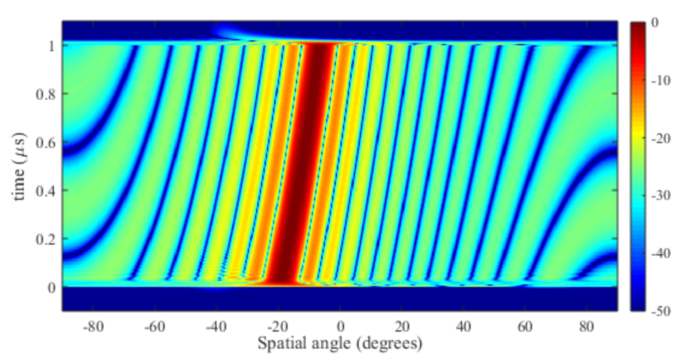

Fig. 6. Far-field of a 20 element slotted Clarricoats-Waldron waveguide (with the dimensions and dispersion relation as shown in Figs. 3 and 4) that is fed with an upchirped LFM waveform (with 100MHz bandwidth centered at 10GHz and pulse duration 1μs).

Poynting vector vanishes. This power flow reversal results in the low-group velocity regime observed in Fig. 4. The bottom panel in Fig. 5 shows the perturbed field distribution when a side-slit is opened on the vertical conductive wall in order to allow the structure to radiate.

For example, Fig. 6 illustrates a far-field emission generated by a 20 element slotted Clarricoats-Waldron waveguide (with the dimensions and dispersion relation as shown in Figs. 3 and 4) that is fed with an upchirped LFM waveform (100MHz bandwidth centered at 10GHz and pulse duration 1μs) in which the fast-time spatial modulation is a linear beamsteering during the pulse. Such a mode may have utility in some tracking applications by mimicking the fixational movement of the human eye [6-8] to modify the delay/angle ambiguity function in an adaptive/cognitive manner. The delay/angle ambiguity function [7] for the same configuration as in Fig. 6 is shown in Fig. 7.

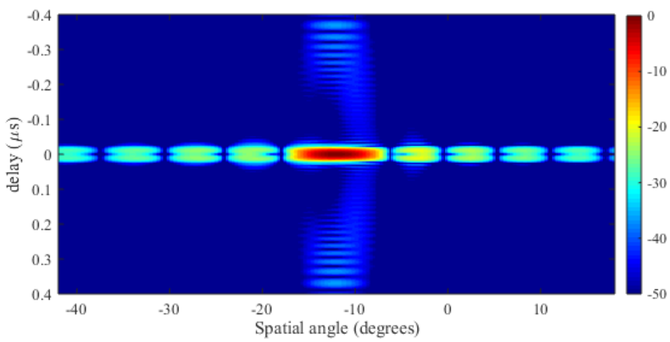

Fig. 7. Delay-Angle Ambiguity Function of a 20 element slotted Clarricoats-Waldron waveguide (with the dimensions and dispersion relation as shown in Figs. 3 and 4) that is fed with an upchirped LFM waveform (with 100MHz bandwidth centered at 10GHz and pulse duration 1μs).

IV. High Power Configuration and Planar Array Generalization

The configuration in Fig. 2 is not directly suitable for high-power applications, because of the small physical cross-section of the waveguide. Exploiting modal symmetries and the Uniqueness Theorem [28] (as discussed in detail in [26]), a composite Clarricoats-Waldron waveguide with multiple dielectric cores can be obtained (as shown in Fig. 8 for the specific case of 9 dielectric cores), therefore enlarging the waveguide cross-section in order to reduce the electric field intensity for a given input power. Such approach prevents dielectric breakdown and increases the power-handling capabilities of the structure linearly with the number of dielectric cores.

SMMArT could also be generalized to a planar grid comprised of a set of N horizontal serial feeds, each composed of N elements, and a similar set of N vertical serial feeds, each likewise composed of N elements as schematically shown in Fig. 9. At the intersections the signals could be combined or perhaps drive dual-polarized elements. In this manner the joint design space includes $2N$ physical waveforms (with their own design dimensionality dependent on their time-bandwidth product) and a transmission line network of N^2 segments and antenna elements, thus providing the possibility for numerous physical emission schemes via the extremely high degrees of freedom involved. Further, the interaction between the physical waveforms over the array aperture could be used as a means to control the excitation of the individual radiating elements, effectively serving as a means to reconfigure the feed-network topology without additional active hardware elements.

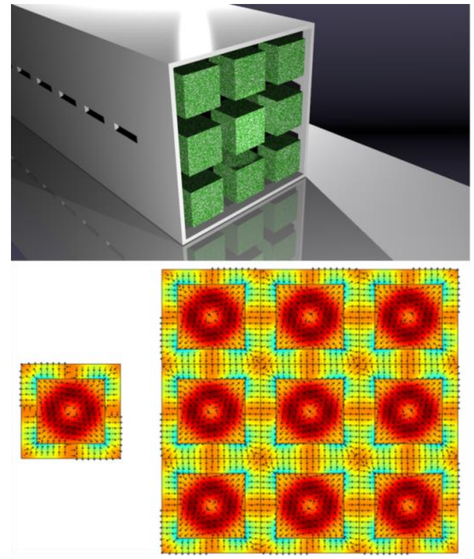

Fig. 8. Composite slotted Clarricoats-Waldron waveguide layout, with modal distribution of the unit cell and of the full structure.

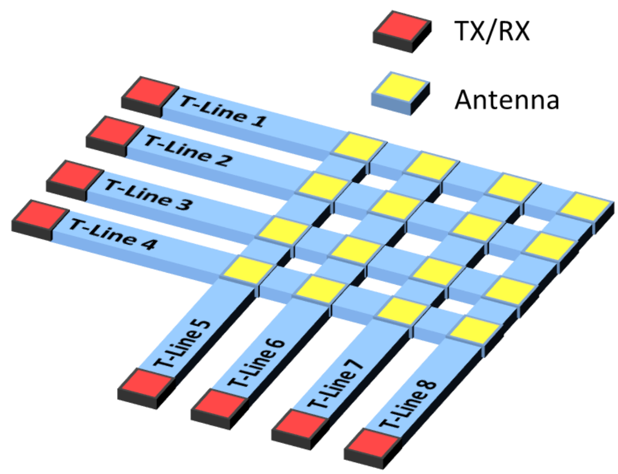

Fig. 9. Two-dimensional generalization of the SMMArT concept

V. Conclusions

The Spatially Modulated Metamaterial Array for Transmit (SMMArT) concept is a metamaterial-based MIMO radar formulation conceived to provide a waveform-dependent radiation pattern by exploiting a novel antenna architecture that relies on slow-group-velocity waveguides. This structure facilitates joint consideration of the waveform(s) and antenna structure as one way in which to enable holistic radar design.

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