Dispersion Engineering for High Power Microwave Amplifiers

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***Abstract*— The design and development of high power microwave (HPM) sources has evolved over the years. From the genesis of the field in the late 1960s until the early 1990s the experimentalists led the way. This was the era driven by researchers striving to achieve ever-greater output power levels. Then a paradigm shift occurred in the early-to-mid 1990s. During this period virtual prototyping evolved to such an extent that particle-in-cell computer simulations of devices overtook the experimentalists in paving the way to new source concepts. Today prospective source concepts are thoroughly explored through virtual prototyping and hardware is built only after simulation results have identified a truly worthy design. We are now entering a new era in HPM source design, where for some applications high power amplifiers are preferred over high power oscillators. In this regard, exploiting metamaterials and photonic bandgap structures may lead to novel beam-wave interactions for amplifiers, in other words, dispersion engineering. This paper presents an overview for the prospects of novel HPM amplifiers using dispersion engineering. Initial concepts that are being explored will be described and plans for initial experiments will be outlined.**

Keywords—high power microwave sources, high power amplifiers, metamaterials, photonic bandgap structures.

I. Introduction

Vacuum electron sources (VEDs) of high power microwave (HPM) fields have been evolving since their inception in the late 1960s. The state-of-the-art in the practice of such sources has been led by intense beam-driven oscillators whose output scale as Pf^2 where P is the peak output microwave power and f is the operating frequency [1]. This is the so-called Figure-of-Merit (FOM) for HPM sources [2]. To-date there has been less interest in HPM amplifiers and this leaves open an opportunity for considerable advances to be made. A comparison of the state-of-the-art oscillator and amplifier in terms of the FOM can be made between Haystack radar's gyrotron amplifier at 94 GHz, 55 kW output power (5.5 kW average), 1600 MHz bandwidth, yielding a FOM 4.9×10^8 W-GHz^2; and ITER/DIII-D's plasma heating gyrotron oscillator at 110 GHz, 1 MW (10 s pulse), 1.1 MHz bandwidth, with a FOM 1.2×10^{10} W-GHz^2. Thus, there is a two order-of-magnitude opportunity to advance the FOM in high power amplifiers with considerable bandwidth.

Over the past decade, periodic structures of readily available materials have been shown to exhibit novel electromagnetic properties [3,4]. Among these periodic composites, negative index metamaterials (NIMs) have been considered for sub-wavelength focusing and lenses with greater sensitivities [5-7]. Several miniature RF devices (*e.g.* phase shifters, couplers and antennas) were also proposed based on printed realizations of NIMs [7-9]. However, NIMs have been plagued with high losses and, as can be concluded from a recent *Proceedings of the IEEE* [10] issue on metamaterials and in a recent book by Volakis *et al.* [11] only simple versions of NIMs have been successfully used in practice and mostly for phase shifters. A significant number of publications based on electromagnetic band gap (EBG) structures have shown the ability to control wave dispersion [12,13]. Specifically, EBGs have been used to realize high impedance ground planes for conformal antenna applications [14-17].

This paper presents the research plan of a Multidisciplinary University Research Initiative (MURI) team that has been recently awarded a 5-year grant to study HPM amplifiers invoking novel dispersion engineering. Metamaterials and EBG structures are of interest for VEDs as such structures provide for wave velocity control critical to realizing high power traveling wave tubes (TWTs) and dielectric Cerenkov maser amplifiers/oscillators. However, as noted by Shiffler *et al.* in [18], dielectrics become vulnerable to charging, resulting in device failure. In spite of these limitations, they note that it is important to *"... explore and exploit the unique physics of relativistic electron beam driven metamaterial devices. The key advance manifested here consists of the concept of finding a metallic sub-wavelength structure, or metamaterial, that mimics the response of a dielectric for generating slow electromagnetic waves."* Indeed, in the same article the authors demonstrated for the first time the use of all-metal metamaterials to generate Cerenkov-like masers interactions.

The remainder of this paper is organized as follows. Section II describes theoretical motivations for using metamaterials and EBGs in HPM sources. Section III presents some of the concerns posed by using metamaterials in high electric field environments. The conclusions are presented in Sec. IV.

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II. THEORETICAL RESEARCH ON METAMATERIALS FOR BEAM-WAVE INTERACTION STRUCTURES

The starting point for this basic research program is to consider the use of metallic metamaterial structures for the beam-wave interaction region that emulate the behavior of dielectric/composite metamaterials. Researchers at Ohio State University and UC Irvine were able to develop non-dielectric versions of typical volumetric dielectric metamaterial structures [19-24] that support the same slow modes as those predicted by volumetric structures [25-27]. That is, these metamaterial structures can be designed to have the same properties (wave slow down, amplification, and field growth) as already noted elsewhere, but do not suffer from charging and surface breakdown [18,28]. Another unique aspect of these proposed metallic metamaterials is their larger bandwidth already demonstrated by realizing small and very large bandwidth antennas (as much as 30:1) [29,30]. Doing so without dielectrics will have transformational impact in realizing HPM devices that are smaller, reconfigurable, and still highly efficient. These proposed wideband metamaterials will also support narrow and chirped pulses for HPM sources. We remark that, to our knowledge, the metamaterial structures recently published by the Ohio State group [30] are the only ones exhibiting large and controllable bandwidth.

A. TWT Interaction with Frozen Modes - Superamplification

Our initial device will be based on a traveling wave tube (TWT) interaction. When an electron beam is injected along the TWT axis, the electromagnetic mode accelerates some electrons and decelerates others, causing bunching. The beam with formed electron bunches moving forward at speed transfers energy to the electromagnetic mode. The resulting increase of the field inside the TWT causes even greater electron bunching, leading to amplification. The amplification efficiency depends sensitively on the electromagnetic traveling wave relative to the space charge wave (SCW) on the electron beam. Synchronism between the electromagnetic mode and SCW is determined by their phase velocities.

An important new feature of our approach is a very special choice of the electromagnetic mode, namely a frozen mode [31]. The frozen mode occurs in a periodic waveguide with the dispersion relations engineered to have a degenerate band edge (DBE). The corresponding DBE mode has a number of extraordinary properties that greatly increase the total amplification factor, a phenomenon referred to as super amplification (Fig. 1). Namely, the DBE mode features an extraordinarily high Q and an extraordinarily high field profile (Figs. 2 and 3). The DBE mode interacts with the beam to create an environment where the EM energy remains far longer in the amplification area. At the same time the beam is exposed to much higher fields, corresponding to large values of the field magnitude profile of the mode. These factors are in addition to the regular amplification mechanisms, justifying the terms super amplification and super bunching.

As to the frozen mode regime, it is a qualitatively new wave phenomenon – it does not reduce to any known electromagnetic resonance and for this reason differs significantly from any oscillator or amplifier-type HPM device based on a conventional resonance. This is associated with singularities in the dispersion relation, such as a stationary inflection point, DBE, or split band edge. The frozen mode regime naturally possesses a number of features beneficial to HPM devices: (i) enhancement of light-matter interactions; (ii) the frozen mode regime can be combined with a common slow wave resonance, resulting in a giant transmission resonance with Q's two orders of magnitude higher compared to that of a regular Fabry-Perot resonance; (iii) since the frozen mode regime is determined entirely by the dispersion relation it can be adapted to modulated waveguides, periodic arrays of resonators, and other structures. The theory proving the existence and properties of the frozen mode regime is well established by now, see [32-35]. Unlike the standard mode interaction in a TWT, the regular band edge and DBE frozen mode regime have a much stronger field buildup at the axis the TWT. The field grows much stronger in the DBE than in the regular band edge case, and the field at the end point is well matched to the outside world.

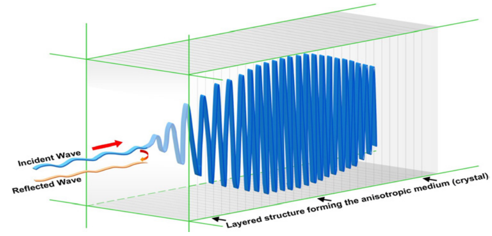

Figure 1. Depiction of wave slow down and amplitude growth (amplification) as the wave propagates within the metamaterial structure (to the right) formed by DBE crystals. (Courtesy J. Volakis, Ohio State University.)

The challenge here is to explore and harvest its superior frequency and bandwidth, dimensions and efficiency for the benefit of the HPM device. The frozen mode regime must be realized using a structure that is able to interact with the electron beam.

There are numerous ways to configure the TWT and its components, as shown in Figs. 3 and 4. One can see that the configurations in Fig. 3 are analogous to the helix TWT configuration analyzed in great details in [48].

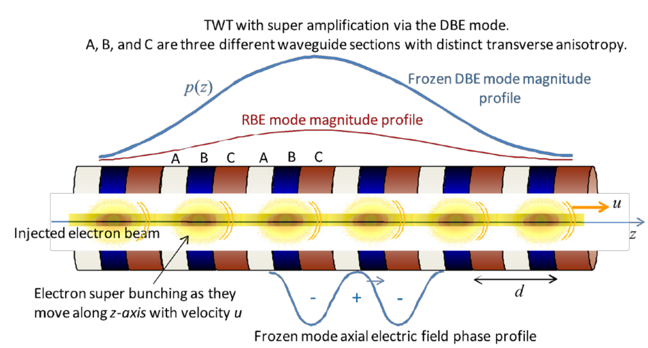

Figure 2. Basic principle of operation. The electron beam transfers energy to the frozen degenerate band edge (DBE) mode. The frozen DBE mode allows for a higher power amplification than the regular band edge mode (RBE). (Courtesy A. Figotin, UC Irvine.)

To fully exploit super amplification the constituent TWT materials and their geometric configurations will be chosen to satisfy a number of specific requirements including, in particular: (i) the alternating electric field pattern of the DBE mode should be optimized for the best electron super bunching; (ii) the wave and beam phase velocities have to be adjusted to maximize the amplification factor; (iii) the metamaterials used have to be broadband and low loss in order to withstand the high fields needed for operation. Optimization of the HPM device to achieve the highest amplification factor is a very complex and sophisticated problem. A theory of an effective nonlinear transmission line-type system capable of accounting for significant features of the wave-beam interaction will be developed and these will be supplemented with particle-in-cell (PIC) simulations.

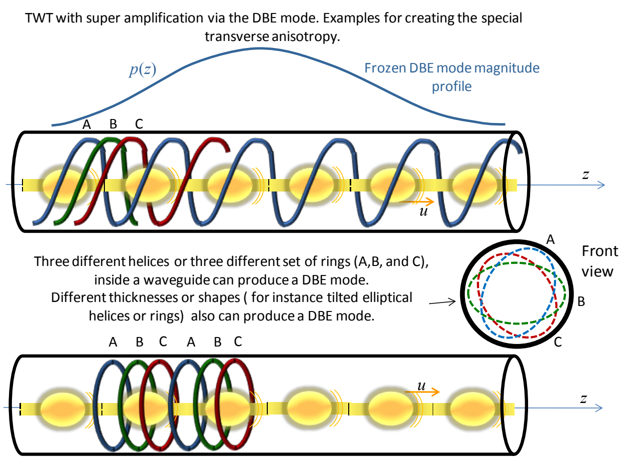

Figure 3. Basic principle of operation. The electron beam transfers energy to the frozen DBE mode. The frozen DBE mode allows for greater amplification compared to the RBE mode. (Courtesy A. Figotin, UC Irvine.)

Well-conceived composite structures can have absorption at least two orders of magnitude less than that of its natural constituents across a broad frequency range, as has been already demonstrated in [37,38]. We will develop a theory of low loss materials that can guide in the search of composites required by the overall requirements of the HPM device.

Tunability can be applied, for instance to the two configurations shown in Fig. 3. In both configurations the electron beam transfers energy to the frozen mode, which is characterized by a mode with zero or almost vanishing group velocity. In both configurations the waveguide boundary conditions are modified by tunable circuits or materials and the mode is no longer frozen. The power moves to the right with a certain speed and is then radiated using an antenna. The operation is engineered by tuning the new group velocity and to release the energy in the TWT with a certain speed. In this way the wavefront shape of the radiated power can be controlled.

The DBE is a very precise operational mode due to its very high Q; hence, it is foreseen that it is easy to change the modal configuration to allow the electromagnetic mode to travel to the output. Various ways are envisioned to alter the boundary conditions: (a) introduce switches, (b) apply an external magnetic field, (c) introduce magnetic coupled circuits, *etc.*, all of which have to be compatible with other components of the HPM device.

Finally, it should be noted that researchers recently discussed the excitation of parasitic waves near cut-off in forward-wave amplifiers and suggested that this might be relevant to metamaterial structures for HPM generation [39]. Their results do not apply to the DBE regime since here the second derivative of the dispersion relation is exactly zero. However, we will extend their analysis to the case of degenerate guided modes, where the derivative(s) of the group velocity is also zero.

B. Metamaterial Structure Concepts for Cerenkov Maser

Here we present ideas how a frozen mode regime mode can be realized to form a high power Cerenkov maser. Clearly, the metamaterial structures discussed earlier provide for (a) low-loss (loss tangents $<10^{-3}$), (b) all-metallic structures to suppress charging and breakdown, (c) controlled operation frequency by adjusting element separation, (d) wideband operation. Therefore, they hold great promise to realize all-metallic Cerenkov-like masers.

As noted by researchers in [18], by "tailoring the characteristics of the artificial dielectric structure, in a fashion not accessible to 'natural' dielectrics, this [electron beam matching to the phase velocity of the slow-guided mode] interaction regime can be greatly expanded over that of standard slow wave structures, such as the variants of the tape helix or disk-loaded devices." Indeed, the proposed metamaterial structures have already been demonstrated to possess this capability. We will consider single and multiple layers to allow for reconfiguration of the coupled RF modes and their frequency of operation. Of course we expect that there will be a tradeoff between wave slow down (*viz.* length of maser) and power handling capabilities.

A prospective Cerenkov maser design based on a frozen mode regime-type DBE mode is presented in Fig. 4. It is clear that the all-metal mode liner provides for much stronger coupling to the beam, as is indicated by the electric field contours. The new degrees of freedom afforded by DBE modes provide for a more effective way to transform axial fields at the center of the guide to vertical ones that propagate within the metamaterial structure. Concurrently, even though the proposed metamaterials do not require vertical grounding pins, such pins may need to be included to prevent charging.

C. Complementary Split-ring Resonators Structures for Cerenkov Maser

The concept for a metamaterial beam-wave interaction structure is based on the design presented by the MIT group in [40]. The proposed structure (Fig. 5) is a complementary metamaterial waveguide built of complementary split-ring resonators. These are cut in a metal plate so that the structure can be fabricated from a metal plate without a substrate. The complementary split ring resonator patch plates are set parallel and form a parallel-plate waveguide. The mode of this waveguide has the electric field component along the waveguide symmetry plane. This longitudinal electric field is suitable for deceleration (microwave generation application) or acceleration (electron accelerator application) of the electron beam traversing down the symmetry plane of the waveguide.

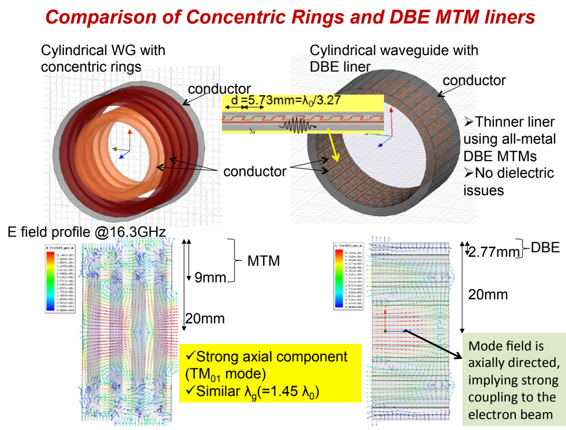

Figure 4. Comparison of concentric ring artificial dielectric structure (left) with frozen mode regime-type degenerate band edge (DBE) mode liners (right) in designing Cerenkov masers. (Courtesy J. Volakis, Ohio State University.)

The structure shown in Fig. 5 was designed to have an infinite extent in the metamaterial plane to simplify calculations. (In the figure, there are 9 unit cells above and 9 below the beam.) A possible closed metamaterial waveguide suitable for an HPM device is depicted in Fig. 6. The metamaterial waveguide surface consists of a periodic chain of complementary split ring resonator cells that allow field propagation in the waveguide. A pencil electron beam from a Pierce gun is employed. The beam will propagate through a channel whose width is about the size of the complementary split ring resonator unit cell (16 mm). A waveguide of this diameter is well below cutoff at S-band. Thus, this design allows for a large reduction in the structure dimensions, which could be very useful in reducing the size and weight of an HPM device.

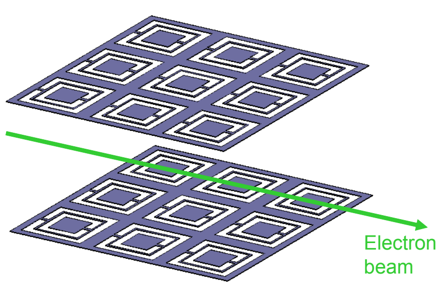

Figure 5. Example of a complementary metamaterial suitable for HPM microwave generation or accelerator applications. For an S-band experiment, the unit cell is 16 by 16 mm and the gap opening is 26 mm. (Courtesy R. Temkin, MIT.)

Preliminary calculations of the gain of an HPM device based on this structure have been performed. A 350 kV electron beam is considered and the intersection of the dispersion curves is the beam-and-MTM-wave interaction point, which occurs at a frequency of f =2.92 GHz with a phase advance of 75 degrees per cell. The metamaterial waveguide mode has negative dispersion. Therefore, an absolute instability of the beam occurs. This type of interaction can be used to build a backward-wave oscillator (BWO). At a value of the current less than the starting current of the BWO, a backward wave amplifier (BWA) can possibly be built.

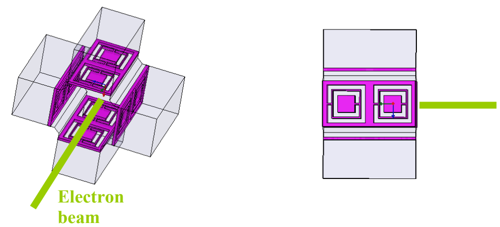

Figure 6. Interaction circuit of a complementary metamaterial-based Cerenkov electron device. The device has been designed for S-band and the unit cell width is 16 mm. (Courtesy R. Temkin, MIT.)

Experiments are planned at both the University of New Mexico and MIT to test the various structures that are proposed and built in actual HPM devices.

III. METAMATERIAL SURVIVABILITY

Recent work at Huddersfield University in the UK studied the response of various metamaterial structures in waveguide as power was flowing. As shown in Fig. 7, the various structures rapidly melted and deformed when subjected to only a few Watts to 10's Watts power level. Clearly traditional metamaterials on substrate are not suitable for HPM applications and new, preferably all-metallic structures need to be designed and exploited for such applications. Researchers at the University of New Mexico will be developing plasma diagnostics to study the early stages of structure breakdown in vacuum.

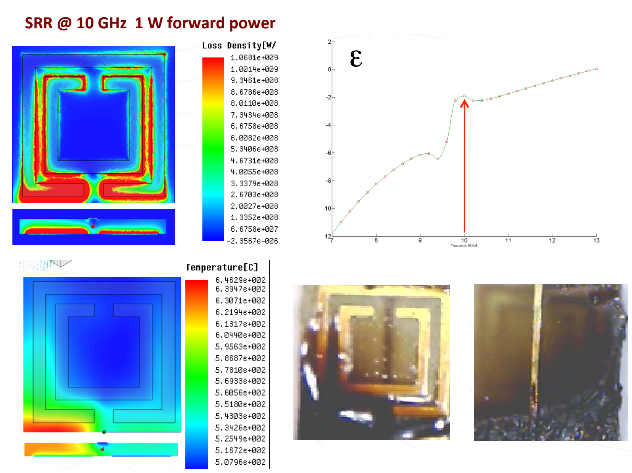

Figure 7. The response of a metamaterial structure on a substrate to 1 W CW illumination at 10 GHz in waveguide. (Courtesy R. Seviour, Huddersfield University, UK.)

IV. CONCLUSIONS

This paper describes a new 5-year basic research program that seeks to exploit dispersion engineering to design novel structures using metamaterials and EBGs. Several candidate structures have been considered, although more comprehensive simulations using particle-in-cell codes have yet to be performed. Experiments designed to study electron beam-wave interaction using such structures are planned at the University of New Mexico and MIT. Finally, the early stages of breakdown of metamaterial and EBG structures *in situ* will be studied at the University of New Mexico using noninvasive plasma and optical diagnostics.

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