Microwave Energy Compressors Utilizing Wave Analog of the Smith-Purcell Effect

Asel Begimova
L. N. Gumilyov Eurasian National University
Astana, Kazakhstan
begimovaasel@gmail.com

Kostyantyn Sirenko
O. Ya. Usikov Institute for Radiophysics and Electronics
Kharkiv, Ukraine
k.sirenko@gmail.com

Vadym Pazynin
O. Ya. Usikov Institute for Radiophysics and Electronics
Kharkiv, Ukraine
vadim.pazynin@gmail.com

Merey Sautbekova
Al-Farabi Kazakh National University
Almaty, Kazakhstan
vinchesterchik@gmail.com

Seil Sautbekov
Al-Farabi Kazakh National University
Almaty, Kazakhstan
sautbek@mail.ru

Nataliya Yashina
O. Ya. Usikov Institute for Radiophysics and Electronics
Kharkiv, Ukraine
yashinanp@gmail.com

Yuriy Sirenko
O. Ya. Usikov Institute for Radiophysics and Electronics
Kharkiv, Ukraine
ORCID: 0000-0001-5276-4596

Abstract**—The paper discusses applications of the wave analog of the Smith-Purcell effect in microwave energy compressors. It is demonstrated that both energy accumulation stage, and switching and release of accumulated energy could benefit from the realization of this effect. A whole new family of compressors featuring the wave analog of the Smith-Purcell effect is establishing, and a couple of novel compressors' designs are presented as examples in this paper.**

Keywords—gratings, electromagnetic energy compression, microwave compressors, planar dielectric waveguides, resonators, short powerful pulses, Smith-Purcell effect

I. Introduction

Microwave or electromagnetic (EM) energy compressors are devices that turn long and low-amplitude input signals into short high-energy output bursts. Compressors find their use in radars, particles accelerators, EM heating of plasma and tissues, EM compatibility testing, and other high-energy EM installations [1]. The working cycle of an active compressor, which is of our interest here, consists of two stages: (1) relatively long accumulation of the input energy in a storage resonator in the form of high-Q oscillations, and (2) much faster release of the accumulated energy [2]–[3].

Often the compressor's output pulse travels some distance in a waveguide before it reaches radiator or some other target. As output pulses could be extremely powerful (up to gigawatt level), and the storage and output segments of compressor assemblies should routinely handle such enormous energies, the requirements to these components are rather tough. Combining compressor and radiator in a single unit as proposed in [4] makes the output waveguides obsolete, eases those requirements, and reduces weight and size of devices, which is advantageous for fabricability. It is even possible to arrange such compressor/radiator units in an array manner for directional radiation featuring beam steering, see [4] for the details. To act as a phased array and exhibit beam steering, each compressor/radiator should be excited and switched right on time with high precision, which is not a trivial task. Inspiration for alleviation of this intricacy is derived from our broad experience with diffraction antennas (aka leaky-wave antennas) [5], [6]. In particular, exciting the array of compressors from one common source via the surface wave of an open dielectric waveguide (just like a diffraction antenna) removes the need for precise timing for each compressor in array. And the wave analog of the Smith-Purcell effect (which manifests itself as the generation of plane EM waves when an open waveguide' surface wave interacts with a periodic grating [5], [7], [8]) allows the directional radiation with beam steering when the array of compressors is treated as a periodic grating. These ideas were tested first as an upgrade of a compressor with open resonator as described next, and implemented in the design detailed in [9], which was the first compressor designed essentially to use the wave analog of the Smith-Purcell effect.

In this paper we speculate first about application of the wave analog of the Smith-Purcell effect in switching and release for compressors on the basis of open resonators. Working oscillation of this type of compressors is sustained between reflecting mirrors and storage resonators usually have no side walls [10], [11]. The storage resonator of the compressor presented in [11] has a dielectric core between its mirrors. Within this core, the field of working oscillations is the most intense. When the compressor is switched to the accumulated energy release, one of the mirrors forming the storage resonator becomes transparent for EM waves, and the accumulated energy leaves the compressor "traveling" along and within the dielectric core. This mode of operation gives rise to an assumption that placing a periodic structure next to this dielectric core could trigger the manifestation of the Smith-Purcell effect. It completely changes the way how the accumulated energy leaves the compressor, allow to control the direction where the compressed pulse goes, and improves the compressor's characteristics. The demonstration of correctness of this idea and its possible implementation is the main contribution of this paper.

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The paper has the following structure: Section II briefly describes the Smith-Purcell effect and what is called its wave analog. Section III presents a couple of novel compressors designs to demonstrate possible applications and usefulness of this effect for design and development of microwave energy compressors.

II. Smith-Purcell Effect and its Wave Analog

The Smith-Purcell effect is the phenomenon of generation of homogeneous plane EM waves via the interaction of a plane, density-modulated electron flow with a nearby one-dimensional periodic grating. The field of electron flow generates the field of plane EM waves [12]–[14]. The characteristics of generated EM waves, such as their number, wavelength and directions of propagation, are determined by characteristics of the electron beam and period of the grating. Explorations of the Smith-Purcell effect greatly contributed to theoretical and applied physics and technology. New classes of devices were created, and numerical simulations of the phenomena paved the wave to the mathematical modeling of diffraction radiation. In turn, these theoretical studies resulted in the insight that the similar effect is observed when the field of inhomogeneous plane EM wave or the field of a surface wave of an open waveguide interact with a nearby periodic structure [5], [7], [8], [15]. And in some cases, these waves generate the same field as a plane, density-modulated electron flow [7] , [15]. This is what the wave analog of the Smith-Purcell effect stands for.

Concordantly, two key components for the realization of the wave analog of the Smith-Purcell effect are (i) an open dielectric waveguide guiding a surface wave, and (ii) an adjacent periodic structure. Two completely different approaches to this composition are presented in this paper. In the first case detailed in Section III-A, the working oscillation of the compressor on the basis of an open resonator is governed by counter propagating waves in its dielectric core. Exposing it to a periodic grating gives rise the wave analog of the Smith-Purcell effect. And in the second case detailed in Section III-B, the array of storage resonators plays the role of a periodic grating, and this structure is fed via an open dielectric waveguide sustaining a surface wave. Its diffraction on the array of storage resonators gives rise the wave analog of the Smith-Purcell effect. Thus, in the first case, a periodic grating is placed inside the compressor and the role of an open dielectric waveguide is played by a resonator's structural part, and in the second case, a set of compressors plays the role of a periodic structure with an open dielectric waveguide outside.

III. Utilizing the Effect in Compressors

The section presents two proof-of-concept examples of compressors featuring the wave analog of the Smith-Purcell effect. In the first case, an existing compressor is upgraded with a grating to use the effect for changes in the accumulated energy release. And in the second case, novel compressor assembly is purposefully designed with the effect in mind.

A. Compressor with Open Storage Resonator

Consider the compressor similar to the one detailed in [11]. It is based on an open resonator formed by two parallel metal mirrors with a dielectric core between them. It is coupled with a feeding waveguide via thin beyond-cutoff window, see Fig. 1 but ignore the green grating so far. The geometric parameters are set as following: the length of the dielectric core (distance between the mirrors) is 8 cm, it is made of Teflon with $\varepsilon = 2.1$, the width of the feeding waveguide and the dielectric core is 1.02 cm, the mirrors width is 5.22 cm, the thickness of the mirrors and the feeding waveguide walls is 0.1 cm the coupling window is 0.22 cm wide, and its thickness is 0.02 cm. With these geometric parameters, the working oscillation of the compressor is $H_{0,1,13}$, its working wavelength is 1.66 cm which approximately corresponds to 18 GHz. The compressor is excited by a sinusoidal TE_{01} signal from the feeding waveguide whose frequency coincides with the working one. When the excitation ends and the compressor is switched from the energy accumulation into energy release stage, the upper mirror becomes transparent for EM waves and the accumulated energy is radiated in the axial direction.

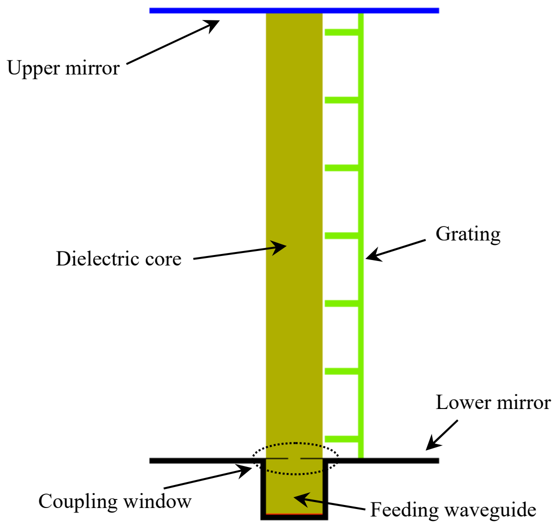

Fig. 1. Geometry of the compressor upgraded with a grating

The working oscillation of this compressor is shaped by counter propagating waves in the dielectric core, which could be considered as an open dielectric waveguide. The idea is that exposing it to a periodic grating during the energy release stage should create a new way of the accumulated energy release in the form of a well-directed pulse due to the wave analog of the Smith-Purcell effect. Indeed, the exponentially decreasing field of the surface wave of the open dielectric waveguide interacts with a nearby periodic grating and generates a volume wave outgoing into the grating's reflection zone. As the described next proof-of-concept numerical experiment shows, this is correct assumption. It worth to note here, that this idea was inspired by our past experience with diffraction radiation antennas. The theory of diffraction antennas is well developed, and the corresponding methods could be used for optimization of parameters of the radiated pulse.

Now, let the compressor described above is equipped with the adjacent periodic grating, it is shown green in Fig. 1. The grating's geometric parameters are following: its period is 1.22 cm, the grooves' width is 1.12 cm, the grooves' depth is 0.62 cm, the distance between the grating and the dielectric core is 0.04 cm. The grating is symmetric to cater for the working oscillation's counter propagating waves in the dielectric core. As the grating is used only for the accumulated energy release, it should not reveal itself during

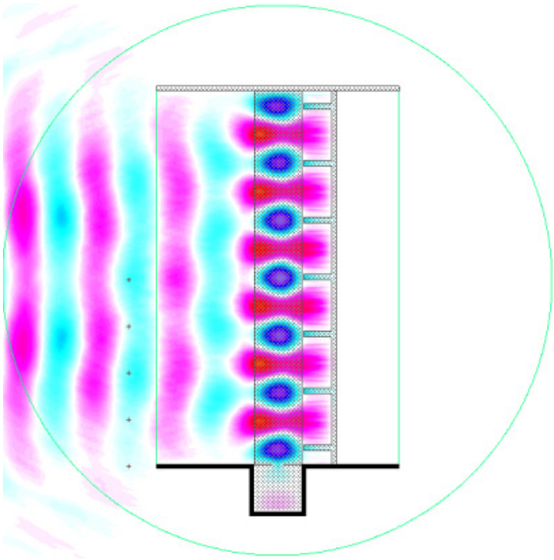

Fig. 2. Accumulated energy release, flat-front radiated pulse, field pattern of E_x component

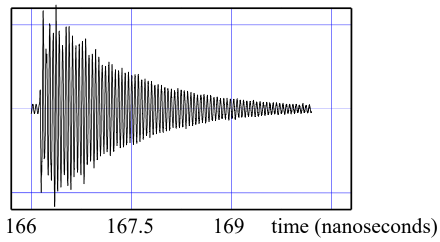

Fig. 3. Amplitude of the radiated pulse

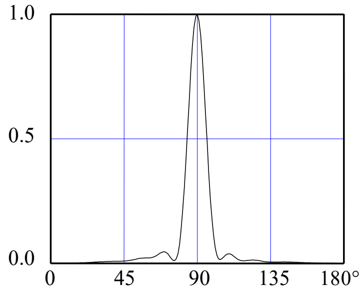

Fig. 4. Normalized radiation pattern

the energy accumulation stage, and appear only during the energy release. For it, the grating is made transparent for EM waves during the energy accumulation. When the compressor is switched to the energy release, its conductivity rises from zero to 5.7×10^{4} within few time steps. In the same time, the upper mirror remains nontransparent throughout the whole duration of the experiment. The moment the grating is introduced into the field of working oscillation, a spatial harmonic with flat front is generated, which travels in the direction normal to the compressor's axis, Fig. 2.

Upgrading the compressor with the grating completely changes the mechanics of the accumulated energy release, thus, direct comparison of characteristics involving the compressed pulse length between the initial and upgraded compressors is not illustrative. In general, the upgraded compressor has good characteristics: for the excitation of 1.66×10^{-7} s, the compressed pulse duration is 4.33×10^{-9} s (Fig. 3), energy efficiency is 0.61 (against 0.38 for the initial compressor), compress ratio is $1.66\times10^{-5}/4.33\times10^{-7}\approx38.3$, power gain is $0.61\times38.5\approx23.4$. More than 97% of the accumulated energy is emitted into the free space as a short and powerful pulse with almost flat front, Fig. 2 and Fig. 3. The radiated pulse is well directed, its main lobe is oriented normally to the axis of compressor, and the width of main lobe does not exceed $12°$, Fig. 4. This coincides perfectly with theoretical predictions [6].

B. Array of Compressors/Radiators

Although, the device discussed in what follows was studied in details in [9], it should be mention here as the first compressor designed to have the wave analog of the Smith-Purcell effect as an essential constituent of its operation.

The device has the following construction, see Fig. 5 and [9]. An array of identical storage resonators forms a periodic structure with the period 1.8 cm. Each storage resonator is a segment of plane-parallel metal waveguide with the width 1.5 cm and height 2 cm. The array has a planar dielectric waveguide in the bottom, the waveguide's width is 1 cm, it is made of Teflon with $\varepsilon=2.1$. The storage resonators are fed via the coupling windows 0.22 cm wide and 0.02 cm thick by a slow wave, which is guided by the dielectric waveguide. The phases of oscillations in the storage resonators differs by a constant value governed by the moderating coefficient of the slow wave and the array period. The array has a dielectric screen on the top with the thickness 0.3 cm. It acts as a switch between the energy accumulation and release stages. During the energy accumulation, the screen is nontransparent for EM waves, and the storage resonators are locked. When the device switches to the energy release, the screen quickly becomes transparent allowing the accumulated energy to be radiated in pre-defined directions as a short and powerful EM pulse.

The device radiates the accumulated energy like phased array antennas or some diffraction antennas. But in contrast with the phased arrays, the storage resonators are excited not individually but simultaneously from one common source like diffraction antennas.

Fig. 6 shows field patterns during the accumulated energy release (the device was excited by a sinusoidal TE_{01} signal with the frequency 12.44 GHz, the duration of excitation is about 1.0×10^{-7} s, the duration of compressed pulse is about 0.8×10^{-9} s). Fig. 7 plots the normalized radiation pattern. It has two lobes, which means that the construction is not optimal and could be improved [9]. Still the directions of the measured lobes are in good agreement with the theoretically predicted ones.

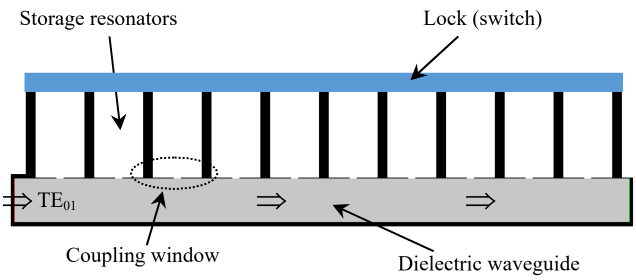

Fig. 5. Geometry of the compressors array

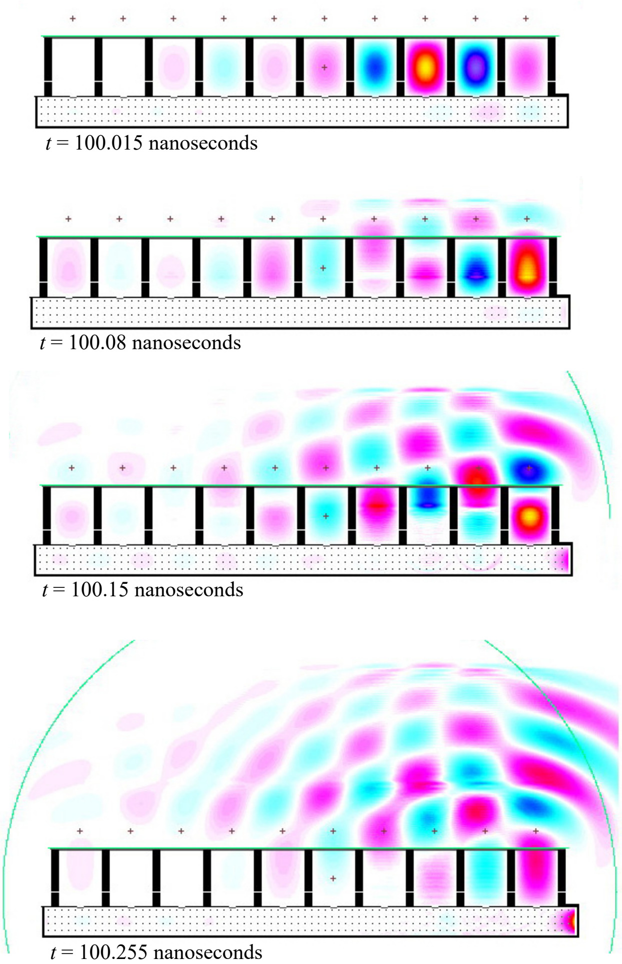

Fig. 6. Various moments of the accumulated energy release, field patterns of E_x component

IV. Conclusion

As it was assumed in [9], continuation of the work with the wave analog of the Smith-Purcell effect could be fruitful and beneficial for the design and development of microwave energy compressors. Indeed, a couple of applications of this effect was devised and presented in this paper. We believe that various compressors' designs could benefit from utilization of the effect, and it is quite possible that more new designs will follow. The growing number of compressors' designs featuring the wave analog of the Smith-Purcell effect allows us to state that a whole new family of compressors is establishing.

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Untimely death of Yuriy Sirenko prevented him from checking the final version of this paper, but his contribution to this work cannot be overestimated.

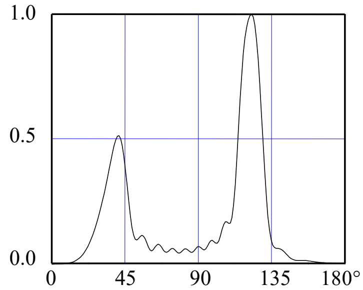

Fig. 7. Normalized radiation pattern

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