On Energy Transfer by Electromagnetic Waves and Its Speed

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Abstract. *It would seem that the processes of radiation and reception of electromagnetic waves, the phenomenon of diffraction and interference are well studied. However, even here there are errors in the interpretation of phenomena. If the error is not corrected immediately, it gradually turns into a prejudice. One such error is the belief that "group velocity" is the rate of energy transfer. In this article, we will correct this erro***r.**

Key words:*phase velocity, group velocity, energy transfer rate, TE and TM modes*

I. Instead of introduction: Energytransferbytransverse electromagnetic waves(TEMmode)

The question of the propagation of energy by TEM modein a monochromatic electromagnetic wave in a homogeneous medium with dispersion has a simple solution [1]. Let there be an infinite homogeneous medium. Letthemonochromaticwave ofTEMmode propagates in this medium. The rate of energy transfer is easily calculated using the Poynting energy conservation law

$$\mathrm{div}\mathbf{S} + \frac{\partial w}{\partial t} = 0\,, \tag{1}$$

where$w = \{\varepsilon(\omega)E^2 + \mu(\omega)B^2\}/2$ is the energy density of the wave,$\mathbf{S} = [\mathbf{E}\times\mathbf{H}]$ is the flux density of the electromagnetic wave.

The rate of energy transfer is

$$\mathbf{v}_e = \frac{\mathbf{S}}{w} = \frac{2[\mathbf{E}\times\mathbf{H}]}{\{\varepsilon(\omega)E^2 + \mu(\omega)B^2\}}\,. \tag{2}$$

Let us show that the energy transfer speedon of diffraction and interference are well studied. However, even here there are errors in the interpretation of phenomena. If the error is not corrected immediately, it gradually turns into a prejudice. One such error is the belief that "group velocity" is the speedon of diffraction and interference are well studied. However, even here there are errors in the interpretation of phenomena. If the error is not corrected immediately, it gradually turns into a prejudice. One such error is the belief that "group velocity" is the rate of energy transfer. In this article, we will correct this error of energy transfer. In this article, we will correct this error TEM of the wave $\mathbf{v}_e$ is equal to the phase velocity of the electromagnetic wave. It is known that the fields **E** and **H** of a plane wave in a homogeneous medium are related by the expression

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$$\mathbf{E} = \sqrt{\frac{\mu(\omega)}{\varepsilon(\omega)}}\mathbf{H}\,. \tag{3}$$

Taking into account expression (3), we obtain from equation (2) the following equation

$$\mathbf{v}_e = \frac{1}{\sqrt{\mu(\omega)\varepsilon(\omega)}} = \mathbf{v}_p(\omega)\,. \tag{4}$$

Thus, the rate of energy transfer by a plane wave in an unbounded medium is equal to the phase velocity of propagation of a monochromatic wave$\mathbf{v}_e = \mathbf{v}_p$. This relation *does not depend* on the form of the dispersion of the medium (normal dispersion or anomalous dispersion).

Now we consider the transfer of energy for simplicity by a periodic sequence of short electromagnetic pulses. The spectrum of such a sequence is discrete. By virtue of the principle of superposition, each wave of the spectrum carries energy with its phase velocity.With normal dispersion, the pulses move from the source at a group velocity. This speed is usually considered to be the rate of "energy transfer. This is "obvious" because the energy is concentrated in each impulse. But as soon as we consider a medium with an anomalous variance, a paradox arises.

Let the periodic sequence of pulses move from the generator to the receiver. The frequency spectrum of this sequence is discrete. The spectrum consists of a set of monochromatic waves. We know that even in the presence of normal dispersion, all the monochromatic components move in one direction with their phase velocities.However, with anomalous dispersion, the pulses will move toward the pulse generator. There is a contradiction in the explanation. On the one hand, each monochromatic wave carries energy from the generator. On the one hand, it seems to us that the impulses move to the generator. *They seem to carry* energy in the opposite direction. This is not the only problem [2].

We are forced to suspect that the statement "*group velocity is the speed of energy transfer by a wave*" is erroneous.

II. Groupspeed

At present, it is considered that the rate of energy transfer by a wave is equal to the group velocity of the wave in the medium where it propagates. This opinion is based on an "obvious" fact. In the propagation of an electromagnetic pulse, all of its energy is concentrated in the region where the wave amplitude (envelope of the pulse) is nonzero. There are paradoxes that do not have convincing explanations. Let us give an example.

Example. Let us consider two waves with the same polarization propagating in a homogeneous medium with dispersion in one direction along the z-axis. For simplicity, we shall assume that their amplitudes are equal, and the frequencies are close$\omega_1 - \omega_2 \ll \omega_2$. Thetotalfieldstrengthis

$$E = E\cos(\omega_1 t - \gamma_1 z) + E\cos(\omega_2 t - \gamma_2 z)$$
$$= 2E\cos\left(\frac{\Delta\omega}{2}t - \frac{\Delta\gamma}{2}z\right)\cos\left(\frac{\omega_1+\omega_2}{2}t - \frac{\gamma_1+\gamma_2}{2}z\right), \quad (2.1)$$

whereω is the frequency, and $\gamma(\omega)$ is the propagation constant of the signal in the medium.

The first cosine in expression (2.1) determines the beat amplitude (the envelope of the total signal). The envelope of the total signal, as follows from the formula, moves in space with a group velocity

$$v_g = \frac{\Delta\omega}{\Delta\gamma}, \quad (2.2)$$

where $\Delta\omega = \omega_1 - \omega_2$; $\Delta\gamma = \gamma_1 - \gamma_2$.

The second cosine of expression (2.1) determines the phase velocity of the total wave

$$v_p = \frac{\omega_1+\omega_2}{\gamma_1+\gamma_2}. \quad (2.3)$$

Here we are dealing with the interference of two waves having close frequencies.We want to note that the waves do not interact with one another and the Poynting vector of each wave carries energy along the z-axis independently of the other wave. The direction of the Poynting vector of each wave coincides with the direction of the phase velocity vector of each of the waves.

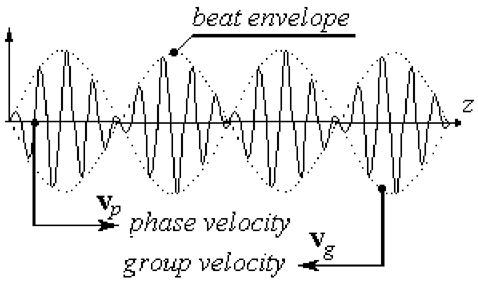

Fig.1 Addition of two oscillations under anomalous dispersion.

The envelope of the interference pattern moves with the group velocity. Its velocity depends on the dispersion of the medium in which the wave propagates. The direction of the group velocity vector can coincide with the direction of the phase velocity (normal dispersion) or be directed in the opposite direction (anomalous dispersion),$-\infty \leq v_g \leq +\infty$.

Thus, to identify the concept of "group velocity" and the speed of energy transfer by the wave is incorrect for the following reasons:

1) First, the concept of "group velocity" fundamentally**is not applicable** to a monochromatic wave in a homogeneous medium (there is no "group of waves").

2) Secondly, this concept of "group velocity" generally **has nothing to do** with the transfer of energy by an electromagnetic wave, but refers to the movement of the envelope.

Thus, the concept of "group velocity" is not applicable to electromagnetic waves in homogeneous media.

One can give the following interpretation of the content of the concept of "group velocity". We know that there is an interference pattern of the first kind. It arises on the plane when it is irradiated with two coherent sources. An interference pattern of the second kind arises when two waves or more with close frequencies propagate along one direction. Between the waves there are beats, the amplitude of which propagates with the group velocity.

III. The Energy Transfer Speed Of TE And TM Modes

In addition to the propagation of energy in homogeneous media, there are ways to distribute energy along the guide structures. Examples of such structures are hollow waveguides, dielectric waveguides, slowing structures [3], etc. Below we consider the rate of energy transfer by waves in such structures.

As is known, electromagnetic waves of two types of TE and TM can propagate in the guiding systems. We will give the derivation of the expression for the energy transfer speed of the TM wave and generalize the result to TE type waves, since the proof is the same.

Specification: Modes in waveguides can be further classified as follows:

Transverse electromagnetic (TEM) modes: Neither electric nor magnetic field in the direction of propagation.

Transverse electric (TE) modes: No electric field in the direction of propagation.

Transverse magnetic (TM) modes: No magnetic field in the direction of propagation.

To describe the propagation of a monochromatic wave, we use Hertz potentials [4]. Consider a TM wave propagating along the z-axis. The wave propagation will be considered in orthogonal cylindrical coordinatesξ, η and z. Let $\boldsymbol{\xi}^0, \boldsymbol{\eta}^0, \mathbf{z}^0$ be the unit vectors.

The Hertz potential satisfies the homogeneous Helmholtz equation

$$\Delta u - \frac{\partial^2 u}{\partial (ct)^2} = \frac{1}{h_\xi h_\eta}\left[\frac{\partial}{\partial \xi}\left(\frac{h_\eta}{h_\xi}\frac{\partial u}{\partial \xi}\right) + \frac{\partial}{\partial \eta}\left(\frac{h_\xi}{h_\eta}\frac{\partial u}{\partial \eta}\right)\right] + \frac{\partial^2 u}{\partial z^2} - \frac{\partial^2 u}{\partial (ct)^2} = 0, \tag{3.1}$$

where$h_\xi(\xi,\eta)$ and $h_\eta(\xi,\eta)$ are the Lame coefficients.We seek the potential u in the following form, $u = U(\xi,\eta)e^{i\omega t - i\gamma z}$, where$k = \omega/c$, $\gamma = \omega/v_p$, v_p is the phase velocity of the wave, $U(\xi,\eta)$ is the amplitude of the Hertz potential.

The amplitudes of the fields **E** and **H**are expressed in terms of the Hertz potentials U [4] as follows:

$$E_\xi = \frac{1}{h_\xi}\frac{\partial^2 U}{\partial\xi\partial z} = -\frac{i\gamma}{h_\xi}\frac{\partial U}{\partial\xi};\; H_\xi = \frac{i\omega\varepsilon}{h_\eta}\frac{\partial U}{\partial\eta}$$
$$E_\eta = \frac{1}{h_\eta}\frac{\partial^2 U}{\partial\eta\partial z} = -\frac{i\gamma}{h_\eta}\frac{\partial U}{\partial\eta};\; H_\eta = \frac{i\omega\varepsilon}{h_\xi}\frac{\partial U}{\partial\xi} \qquad (3.2)$$
$$E_z = k^2 U + \frac{\partial^2 U}{\partial z^2} = (k^2-\gamma^2)U;\; H_z = 0\,.$$

Consider the field components and write the expressions for the energy density and flux density using the Poynting energy conservation law. We consider separately the energy and the longitudinal energy flux propagating along the z-axis $(w_L, \mathbf{S}_L)$, and the energy and energy flux propagating in the $z = constant(w_T, \mathbf{S}_T)$ plane, i.e. in the perpendicular direction.The energy flux density of an electromagnetic wave (the Poynting vector) is

$$\mathbf{S} = \frac{1}{2}[\mathbf{E}\times\mathbf{H}^*] = \frac{1}{2}\begin{bmatrix}\boldsymbol{\xi}^0 & \boldsymbol{\eta}^0 & \mathbf{z}^0\\ E_\xi & E_\eta & E_z\\ H_\xi^* & H_\eta^* & 0\end{bmatrix} = \frac{1}{2}\left[-\boldsymbol{\xi}^0(H_\eta^* E_z) + \boldsymbol{\eta}^0(H_\xi^* E_z) + \mathbf{z}^0(E_\xi H_\eta^* - E_\eta H_\xi^*)\right]. \qquad (3.3)$$

We see that there are two flows of energy. One flux $(\mathbf{S}_L)$ is directed along the z-axis. The second flux $(\mathbf{S}_T)$ is directed perpendicular to the z-axis.Here and below, the sign (*) means complex conjugation.

$$\mathbf{S}_L = \frac{1}{2}\left[(E_\xi\boldsymbol{\xi}^0 + E_\eta\boldsymbol{\eta}^0)\times(H_\xi^*\boldsymbol{\xi}^0 + H_\eta^*\boldsymbol{\eta}^0)\right] = \frac{\gamma\omega\varepsilon}{2}\left[\left(\frac{1}{h_\xi}\frac{\partial U}{\partial\xi}\right)^2 + \left(\frac{1}{h_\eta}\frac{\partial U}{\partial\eta}\right)^2\right]\mathbf{z}^0. \qquad (3.4)$$

It corresponds to the energy density

$$w_L = \frac{\varepsilon}{4}\left[|E_\xi|^2 + |E_\eta|^2\right] + \frac{\mu}{4}\left[|H_\xi|^2 + |H_\eta|^2\right] = \frac{\varepsilon}{4}(\gamma^2+k^2)\left[\left(\frac{1}{h_\xi}\frac{\partial U}{\partial\xi}\right)^2 + \left(\frac{1}{h_\eta}\frac{\partial U}{\partial\eta}\right)^2\right]. \qquad (3.5)$$

We write down the expression for the speed of energy transfer by a wave along the z-axis.

$$\mathbf{v}_e = \frac{\mathbf{S}_L}{w_L} = \frac{2\gamma\omega}{\gamma^2+k^2}\mathbf{z}^0 = \frac{2v_p\mathbf{z}^0}{1+(v_p/c)^2}\,. \qquad (3.6)$$

Now, in the same way, we determine the flux density and energy density in the plane perpendicular to the z-axis.

$$\mathbf{S}_T = -\boldsymbol{\xi}^0(H_\eta^* E_z) + \boldsymbol{\eta}^0(H_\xi^* E_z) = -i\omega\varepsilon(k^2-\gamma^2)U\left[\frac{1}{h_\eta}\frac{\partial U}{\partial\eta}\boldsymbol{\xi}^0 + \frac{1}{h_\xi}\frac{\partial U}{\partial\xi}\boldsymbol{\eta}^0\right],$$
$$w_T = \frac{\varepsilon}{4}|E_z|^2 = (k^2-\gamma^2)^2U^2. \qquad (3.7)$$

As can be seen from the expression, the speed of energy transfer is:

$$\mathbf{v}_T = \frac{\mathbf{S}_T}{w_T} = -i\frac{\omega\varepsilon}{(k^2-\gamma^2)}\frac{1}{U}\left[\frac{1}{h_\eta}\frac{\partial U}{\partial\eta}\boldsymbol{\xi}^0 + \frac{1}{h_\xi}\frac{\partial U}{\partial\xi}\boldsymbol{\eta}^0\right]. \qquad (3.8)$$

The rate of energy transfer in the plane perpendicular to the z-axis is an imaginary quantity. Consequently, in the plane$z = constant$there is no energy transfer, but there are oscillations (standing waves). These oscillations of the longitudinal component of the electric field E_z. *Phase shiftof these oscillations* along the z-axis creates the illusion that the field E_z moves along the z-axis with the phase velocity v_p.So, we have the final result. The energy of the wave is transferred only along the z-axis with velocity v_e.

$$\mathbf{v}_e = \frac{\dot{\mathbf{S}}_L}{\dot{w}_L} = \frac{2\gamma\omega}{\gamma^2 + k^2}\mathbf{z}^0 = \frac{2v_p\mathbf{z}^0}{1+\left(v_p/c\right)^2};\ \ v_p = \frac{\omega}{\gamma}. \quad (3.9)$$

An analogous result holds for waves of theTE type.

Such waves occur in waveguides, waves in slowing structures, in other energy transmission lines. Belowwewillconsiderexamples.

IV. Examples

Let us illustrate the obtained results with examples.

Example 1. Energy transfer by the TE wave in a rectangular waveguide with a cross section$a \cdot b$. The frequency of a monochromatic wave isω. The waveguide is shown in Fig. 2.

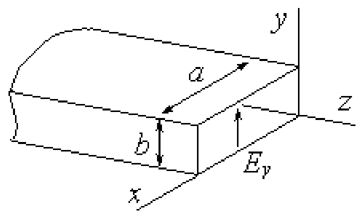

Fig. 2 Rectangular waveguide.

We write the expressions for the fields:

$$E_y = E_0 \sin\left(\frac{\pi x}{a}\right) e^{-i\gamma z};\ \ H_x = -\frac{\gamma}{\omega\mu} E_0 \sin\left(\frac{\pi x}{a}\right) e^{-i\gamma z};\ H_z = \frac{i\pi}{\omega\mu a} E_0 \sin\left(\frac{\pi x}{a}\right) e^{-i\gamma z}, \quad (4.1)$$

where$\gamma = \omega/v_p = (\omega/c)\sqrt{1-(\lambda/2a)^2}$ is the wave propagation constant;$\lambda = 2\pi c/\omega$ is the free-space wavelength($\lambda \le 2a$).The phase velocity of the wave is

$$v_p = \frac{c}{\sqrt{1-(\lambda/2a)^2}}. \quad (4.2)$$

It follows from (4.2) that the speed of energy transfer is

$$v_e = \frac{2v_p}{1+\left(v_p/c\right)^2} = c\frac{\sqrt{1-(\lambda/2a)^2}}{\sqrt{1+(\lambda/2a)^2}};\ v_e \le c \le v_p. \quad (4.3)$$

It follows from expression (4.3) that the velocity of energy transfer by a wave cannot exceed the speed of light.

Example 2. The comb-like slowing structure. A simple two-dimensional flat comb-like structure is shown in Fig. 3.

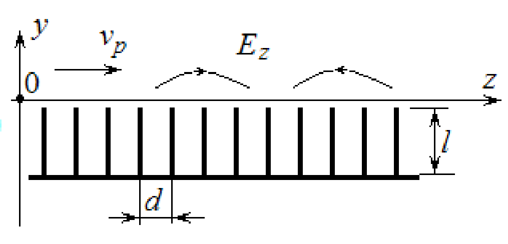

Fig. 3 Comb-like structure.

We write the fields of the wave E above the surface of the structure ($y \ge 0$), taking into account the relation: $d \ll l < \lambda/4$.

$$H_x = He^{-py-i\gamma z};\ \ E_y = -\frac{p^2}{\omega\varepsilon}He^{-py-i\gamma z};\ E_z = -\frac{\gamma}{i\omega\varepsilon}He^{-py-i\gamma z}, \quad (4.4)$$

Where$\gamma = \sqrt{p^2 + k^2} = k/\sin(kl)$is the wave propagation constant along the z-axis, $p = k\cot(kl)$ is the wave attenuation constant in the direction$y \geq 0$;

$$p = \sqrt{\gamma^2 - k^2} = \sqrt{\frac{k^2}{\sin^2(kl)} - k^2} = \sqrt{\frac{k^2[1 - \sin^2(kl)]}{\sin^2(kl)}} = \frac{k\cos(kl)}{\sin(kl)} = k\cot(kl).$$

Thephasevelocityis

$$v_p = \frac{\omega}{\gamma} = c\cos(kl)\,;\; kl = \frac{\omega l}{c} = \frac{2\pi l}{\lambda};\; \gamma = \sqrt{p^2 + k^2} = \frac{k}{\sin(kl)}\,. \qquad (4.5)$$

Now write the expression for the energy transfer speed:

$$v_e = \frac{2c\ \cos(kl)}{1 + \cos^2(kl)}\,; \quad \left(v_p \leq v_e \leq c\right). \qquad (4.6)$$

We see that the energy transfer rate is greater than the phase velocity of the *slow* (delayed)wave. As mentioned above, the E_z-component *does not move* with the wave. This field *oscillates* in a plane perpendicular to the z-axis. For large decelerations of the wave, when$\cos(kl)$ is very small, the group velocity is almost twice the phase velocity of the wave. “Grooves” in the comb-like structure with its field E_z, as it were, prevent the transfer of energy by the wave, delay the transfer of energy.

Now we will explain the term “slow(delayed) wave”.

A slow wave is a special type of wave propagation, usually a controlled wave type, and it is described mainly in the frequency domain. Slow structures are waveguides or transmission lines in which the wave **moves at a phase velocity equal to or less than** some predetermined wave propagation velocity. In other words, a slow wave should be interpreted with respect to its fast wave in comparison with the **reference speed**, such as the speed of light in a hollow metal waveguide.

V. Backward-waveoscillators

Existing model of explanation of phenomena in BWO. Here we consider the application of the results to the theory of a backward-wave oscillator (BWO). First we will consider the modern theory of **BWO**, and then we will describe the new mechanism and compare them. There are two main subtypes of BWOs: BWO-M and BWO-O. (the**M-type (BWO-M)**, and the **O-type (BWO-O)**).

1. Generator BWO-M. The M-type backward wave generator (**BWO-M**) was invented in 1959 by Bernard Epsztein [5]. A schematic representation of the construction of the BWO-M is shown in Fig. 4 .

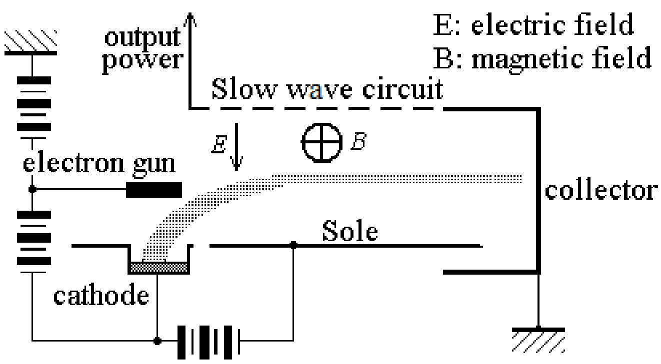

Fig.4 A schematic representation of the construction of the **BWO-M**

The electron beam from the cathode moves with the crossed fields **E** and **H** and moves to the collector. The beam interacts with the waves in the slowing down (delaying) system. There are two waves in the slowing system. A straight wave propagates from the cathode to the collector. It interacts with the wave field. According to modern theory, the energy from the interaction of electrons with the wave returns to the cathode with a group velocity and after reflection it turns into a direct wave. This wave again interacts with the electron beam. The generated oscillation energy is output near the cathode, where, as is the maximum of the field.

2. Generator BWO-O. [6] The O-type backward wave generator has a different design, selected in Fig. 5. Thegeneratorwasdesignedin 1952. One of the creators of **BWO-O** is Rudolf Kompfner. ThegeneratorisshowninFig. 5.

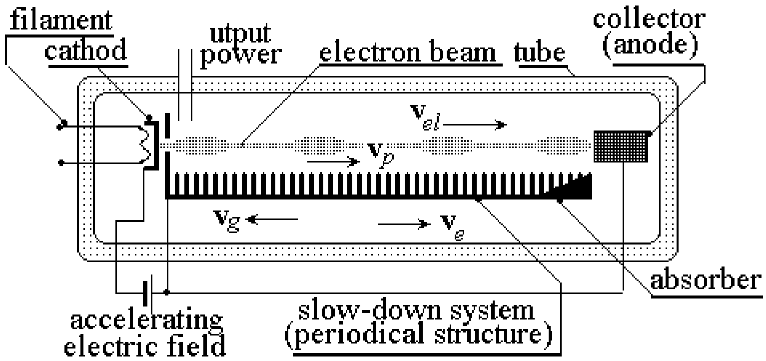

Fig. 5. BWO-O. $\mathbf{v}_p$ is the phase velocity; $\mathbf{v}_{el}$ is the velocity of electrons,$\mathbf{v}_e$ is the wave energy velocity;$\mathbf{v}_g$ is the group velocity.

The principles of the operation of BWO-O and BWO-M are similar. Let us explain the mechanism of excitation of oscillations in BWO-O. The cathode (see Fig. 5) continuously emits electrons that are accelerated by the anode and then move with a constant velocity $\mathbf{v}_{el}$ over the decelerating structure.

The phase velocity of the wave in the decelerating structure $\mathbf{v}_p$ is slightly smaller than the velocity of the electrons. Throughout the trajectory, the electrons interact with the wave. Due to the fact that they transfer a part of the kinetic energy to the wave, their kinetic energy decreases.

The energy that electrons transmit to the wave returns to the cathode from each part of the interaction with the group velocity$\mathbf{v}_g$. A feedback is obtained, which supports the generation of oscillations. The wave reflected from the cathode reacts again with the electron beam. Some of its energy is diverted to the external circuit. The electrons are collected by the collector after the interaction.

A direct wave moving with an electron beam can be reflected from the collector. It is believed that the reflected wave worsens the characteristics of the BWO. Therefore, sometimes at the end of the slowing structure an absorber is installed, which reduces the energy of the reflected wave.

VI. The new model for explaining phenomena

Specialists in the field of microwave electronics and particle accelerators hardly need special comments. Here we summarize the new results, radically changing the existing explanations.

Generators BWO-M and BWO-O. Above, we briefly outlined the principle of operation of the BWO generators. For M-type and O-type devices, it is close. Therefore, we will briefly present a new theory of work, using the example of BWO-O, shown in Fig. 5.

The electron gun consists of a cathode and an anode. The accelerating voltage is applied to the anode. The electron beam from the electron gun moves along the slowing to the collector. In parallel, along the decelerating structure, a delayed electromagnetic wave propagates (TM mode). The velocity of electrons $\mathbf{v}_{el}$ is slightly greater than the phase velocity of the slow wave $\mathbf{v}_p$. Therefore, electrons transmit some of their kinetic energy to the electromagnetic wave.

The velocity of energy transfer by a wave for small $\mathbf{v}_e$ is approximately 2 times higher than the phase velocity $\mathbf{v}_p$. Therefore, the energy of the wave is transported at a velocity $\mathbf{v}_e$ to the collector. Pay attention to the following fact. The group velocity $\mathbf{v}_g$ is directed in the opposite direction (towards the cathode, that is, in the opposite direction!).

The electron stream is collected by the collector, and the amplified delayed wave is reflected and returns to the electron gun. The reflected wave practically does not interact with the electron beam. Part of the energy of the wave through the waveguide is sent to the consumer. The other part of the wave is reflected and moves in the opposite direction, interacting with the electron beam.

We see that the new explanation is fundamentally different from the old ideas.

New constructive and technical capabilities. Since we are now using a new model for explaining phenomena, new opportunities appear for improving the BWO-M and BWO-O generators.

1) We can divert the energy of an electromagnetic wave from any part of the slow-wave system. For example, we can divert energy from the collector part of the device. This is a convenient option from a constructive point of view.

2) Near the electron gun, we can install a device with special properties, reflecting the wave. This device should change the phase of the reflected wave as a function of frequency in such a way as to provide the widest frequency generation region.

Broadband amplifiers [7]. The creation of broadband amplifiers was hampered by the prejudice that energy with group velocity *returned* to the electron gun. This fact could lead, in the opinion of designers, to self-excitation of the amplifier (the amplifier was turned into a generator). For this reason, developers did not actively use slowing down structures with *anomalous* dispersion. However, structures with anomalous dispersion provided the *widest band* of amplification of electromagnetic waves. Now this prejudice is eliminated. Slowing structures with anomalous dispersion can be widely used in engineering.

VII. Conclusion

So, we got the following important results:

1) We have shown that the group velocity has nothing to do with the transfer of energy by electromagnetic waves. Group velocity is the speed of movement of an interference pattern of the second kind. Such a picture arises as a result of interference of a group of waves with different frequencies, which propagate in one direction.

2) The rate of energy transfer in homogeneous media with dispersion is equal to the phase velocity of the electromagnetic wave.

3) We have established that the rate of energy transfer of TE and TM by modes has a common direction with the phase velocity of the mode and depends on it. The speed of energy transfer is $\mathbf{v}_e = 2\mathbf{v}_p/\left[1 + (v_\mathbf{p}/c)^2\right]$. The speed of energy transfer is always less than the speed of light.

4) We note an interesting fact. The field E_z with which the electrons interact, "propagates" with the phase velocity $\mathbf{v}_p$, but this field does not create a longitudinal energy flux. The field oscillates in a plane perpendicular to the propagation direction of the wave.

5) We corrected the errors in the theory of microwave devices and provided a correct description of the oscillation generation mechanism in the devices. (of the M-type BWO-M, and the O-type BWO-O).

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