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Abstract. The problem of surface electromagnetic waves is discussed. In spite of recent experimental evidence for the existence of Zenneck surface waves, theoretical consensus on this issue is lacking.

Surface electromagnetic waves (SEMWs) can be excited at the interface between two or more media. These two-dimensional electromagnetic waves die down exponentially along the third coordinate (height). They are of practical interest because their energy decreases in inverse proportion to the distance from a pointlike source, while the energy of bulk electromagnetic waves (BEMWs) decreases in inverse proportion to the distance squared to the source. In practical work this factor may substantially extend the range of action of radars and communication systems and also increase their efficiency, since the wave is 'anchored' on the surface and 'follows' its curvature.

Many aspects of excitation and propagation of the SEMWs still remain uninvestigated. We know bulk (three-dimensional) electromagnetic waves, slow surface waves, and rapid surface waves, among which the Zenneck surface electromagnetic waves occupy a special place [1]. The theory of these waves was worked out by Zenneck [1] and Sommerfeld [2]. Many physicists both in this country and abroad [3 – 6] have published contradictory data concerning the Zenneck surface electromagnetic waves and go as far as 'proving' theoretically that they cannot and do not exist [7]. The history of studying the Zenneck waves is given in detail in review [8]. Here is the current status of the SEMW problem.

Surface electromagnetic waves can exist at the interface between two media only if the permittivity of one of the media is negative or has a nonzero imaginary part. In the former case, these waves are known as Fano waves and their phase velocity is less than the speed of light; in the latter case, they are called Zenneck waves and their phase velocity exceeds the speed of light [9]. Up until 1980, all experimental work on surface waves was carried out either in gas plasmas in the radio frequency band or in semiconductors and metals in the infrared and optical ranges. In all these cases, Fano modes with a phase velocity much lower than the speed of light were detected, which made it easier to observe them using the frustrated total internal reflection method or a grating deposited on the surface itself. In contrast to Fano modes, the phase velocity of the Zenneck surface electromagnetic waves is greater than the speed of light, which renders the above-mentioned techniques unsuitable. Consequently, the Zenneck surface electromagnetic waves resisted observation for a long time. Furthermore, an opinion existed that they cannot be excited in principle. An additional complication stemmed from the fact that any real source of electromagnetic field located at an interface between two media produces a mixed field composed of surface and bulk waves. Separation of these components is a complicated and difficult experimental task.

A Zenneck wave was detected experimentally in 1989 [8]. The Zenneck wave was separated unequivocally (practically in pure form) from the bulk radiation field in a number of laboratory microwave experiments in salt water; all its main characteristics were measured: phase velocity and attenuation, height of the field localization in air, rate of change of the phase wave along the vertical, and the typical decreasing curve of the wave field as a function of distance. All characteristics were found to be in good agreement with the Sommerfeld – Zenneck theory. We will also point to an experimental work [10] in which the Zenneck surface waves were observed in a solid in the optical range.

Nevertheless, we witness an unusual situation in the theory of the Zenneck waves. It became clear that **depending on the method chosen for solving the problem**, the theory may either support or negate the possibility of the existence of a Zenneck wave in the field of a real emitter.

It was pointed out in monograph [11] that "...the existence of a Zenneck wave depends on the form in which we seek the solution: namely, it exists when the solution is sought as an integral along the cuts in Fig. 4.12 but does not exist when we seek it as the same integral along the cuts in Fig. 4.11...".

In Sommerfeld's work, the wave exists [2]. He gave the solution in the form of a definite integral of a very cumbersome type. To compute this integral at least approximately, Sommerfeld mapped the integration path to the complex plane in the space of wave vectors. The integral then broke down into three components, one of which corresponded to a Zenneck surface wave, and the other two to bulk waves, one in each medium. It is fairly difficult to evaluate the contribution from each component in the general case. Sommerfeld was of the opinion that the surface wave dominated at large distances; he thus established the relation between the surface wave and the radiation source. Weyl's approach [3] leads to a solution in the form of an angular spectrum of plane waves, which is equivalent to Sommerfeld's integral formula but does not contain a surface wave.

Later on, the traditional approach to the problem consisted in using the saddle point approximation to evaluate the Sommerfeld integral. However, Shevchenko [12] showed in 1969 that "...the Zenneck wave is a special

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case of surface waves — a wave existing on a planar conducting surface. The transverse wave number of this wave lies in the third quadrant in the neighborhood of 1, i.e., a Zenneck wave is a rapid wave... . It is of interest to note that if we seek it by the saddle point approximation from the Sommerfeld integral which represents the source field over a planar conducting surface, then we find that the steepest descent path never meets the pole corresponding to the Zenneck wave's wave number... . Therefore, a Zenneck wave is not removed as a residue from the integral. Among other issues, this fact was the subject of discussion between two well-known physicists, H M Barlow and J R Wait [13]. In view of what we said above, Wait expressed doubts that the Zenneck wave may exist in practical situations...''.

Note that this same V V Shevchenko argued in favor of the existence of the Zenneck wave [14] by a different technique: by determining the spectrum of normal waves over the impedance surface. Later on, these results were confirmed by Kistovich [15]. In addition, Yu V Kistovich gave a theoretical proof [16] of the correctness of the problem formulation and experimental conditions [8].

Monograph [17] notes: ''...a Zenneck wave transforms into a plane wave sliding along an ideally conducting plane...'' and ''...Transmitting antennas in fact do not excite the Zenneck surface wave, so that it plays no role in the propagation of radio waves over land or sea. Indeed, the structure of a radio wave field is completely different...'', and ''...a Zenneck wave can be rapid as well as slow... .''

These quotes show that theoreticians are of contradicting opinions about the existence of a Zenneck wave. Obviously, the decisive role is played in such situations by the experiment. Such an experiment was indeed conducted [8]. It might seem that the debate between theoreticians has been successfully concluded. Not quite: A V Kukushkin again stated in 1993 in his article in *Physics – Uspekhi* [7]: ''...Note by the way that the so-called Zenneck wave (the rapid eigenwave) predicted some years ago ... has not yet been observed... .'' However, V A Egorov reported another observation of a Zenneck wave [18] in 2004.

Conclusion: it is necessary to continue theoretical and experimental investigation of surface electromagnetic waves, including the Zenneck surface electromagnetic waves.

Experimental studies run so far [8] have been carried out in the centimeter wave range; for a fuller picture, the frequency range of the investigations needs widening and special attention needs to be paid to the meter wave range.

It is necessary to establish the conditions of excitation and propagation of surface waves in natural environments, which would have great importance for applications and may lead to more efficient converters of electromagnetic waves to surface waves (antennas [19, 20] and some others), surface-wave-based radar stations [21, 22], and communications systems [23]. Furthermore, natural or artificial transmission lines for surface waves can be designed [24], working with higher efficiency than currently available systems.

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