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# Application of Slow-Wave Structures for RF and Microwave Heating

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*Wide application of radiofrequency (RF) and microwave (MW) heating of dielectric materials is restrained by the relatively small specific RF losses and inhomogeneity of the MW energy penetration in the treated objects. These disadvantages may be overcome by using applicators based on slow-wave structures which support modes in which the phase velocity is less than the free-space velocity of light. These structures concentrate the electromagnetic field relatively homogeneously along the system axis. Diverse applications have been found including food heating, disinfecting agricultural products, and electro-coagulation.*

**Keywords:** Applicator, hybrid wave, microwave heating, radiofrequency heating, slowing factor, slow-wave structure.

## INTRODUCTION

Heating technology based on the application of slow-wave structures (SWSs) is described in this paper. SWSs combine properties and advantages of transmission lines and lumped elements, concentrate electromagnetic energy in a given volume, and distribute it homogeneously in the propagation direction, enabling their use with RF and MW sources.

Previously, SWSs were used mostly as delay lines [1] and as interaction circuits in MW vacuum devices, and their properties were studied for these specific applications. Spreading industrial, medical, and military MW applications have encouraged study of SWS properties [2]. Analysis, experiments and practical realization have shown that the SWSs have many previously unknown properties, which can be used for creating novel technologies for measurements, domestic and industrial heating, plasma generation, diagnostics, and physiotherapy [2, 3]. This paper briefly describes the advantages and potential of SWS application for heating.

## DEFINITIONS AND PROPERTIES

Transmission lines in which electromagnetic waves propagate with a phase velocity  $v_p$  less than the light velocity  $c$  in free space are called SWSs. The ratio  $N=c/v_p$  is called the slowing factor. In general, SWSs are formed by two electrodes, one of which, the impedance electrode, is formed by a periodic row of transverse conductors connected in series in the direction of the wave propagation [2]. Although slow waves can propagate

without radiation along one impedance electrode, a second "screen" electrode is used for simplifying the wave excitation and screening its field, if needed.

The main property of slow waves is the proportionality of the energy concentration in the longitudinal direction to the slowing factor  $N$  and its concentration near the impedance conductor surfaces, i.e., the energy is concentrated in a small volume with a characteristic length much less than the free space wavelength. The same energy distribution in the transverse direction can be achieved at different values of frequency by changing  $N$ , or *vice versa*, the energy concentration at constant  $N$  can be changed by changing the frequency.

In the most cases, the boundary conditions on the impedance electrodes are satisfied only by a sum of TM- and TE-waves [4], which exist in the slow-wave structures only together and have the same phase and group velocities. At the same time, these waves behave quite differently at boundaries of dielectric and magnetic materials as well as at anisotropic surfaces. For example, the distribution of the TE-wave in the transverse direction insignificantly depends on dielectric objects placed near the impedance electrode, while the TM-wave distribution changes significantly. The depth of the TE-wave penetration in the absorbing or lossy materials significantly exceeds that of the TM-wave. This effect relates to the transverse distribution in the SWSs and has no relation to the incident waves [5].

Unlike the TM- and TE-waves in waveguides, the TM- and TE-waves in SWSs differ by the electric and magnetic energy stored in each of them - the difference exceeds  $N^2$  times [2]. This property, together with the anisotropic properties of slow waves and the high concentration of energy, makes it possible to significantly increase the heating effectiveness for materials with various electromagnetic properties including high temperature plasma.

Volumetric objects can be heated relatively homogeneously by distributed "pumping" of energy from the slow wave into the treated object. This occurs when the phase velocity  $v_p$  in a SWS exceeds the light velocity  $c_e$  in the surrounding material or object [6]. In the absence of an object, the intensity of the electric and magnetic fields near the open surface of the applicator impedance electrode decreases exponentially with the distance to this surface. In the presence of an object placed parallel to the impedance electrode and separated from it with a gap, and implementation of the inequality  $v_p > c_e$ , a part of the wave energy radiates into the object as a plane wave propagates at an angle to the impedance electrode, depending on the difference in the velocities [6].

#### APPLICATORS BASED ON COUPLED SLOW-WAVE STRUCTURES

Coupled SWSs are formed by two parallel impedance electrodes with mirror configurations (Figure 1). Unlike SWSs with one impedance electrode, the coupled SWSs can be excited in different modes: in-phase and opposite-phase. These modes are characterized by different distributions of TM- and TE-waves in the transverse direction. In the opposite-phase mode, the TM-wave, having most of the electric energy, is concentrated between the impedance electrodes with a relatively homogeneous distribution, and the object to be treated may be placed there.

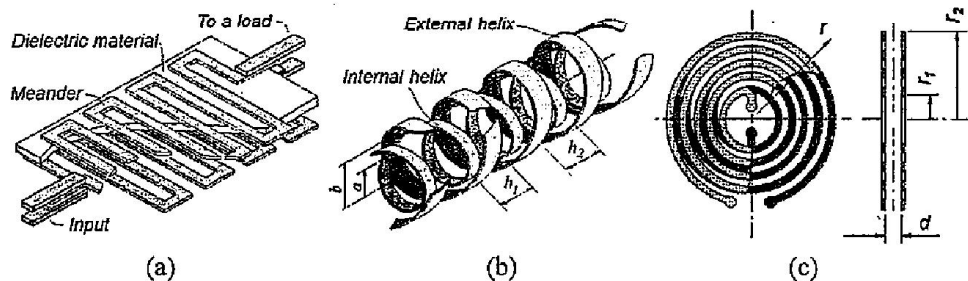


Figure 1. Coupled SWSs: (a) meanders shifted at half-period, (b) coupled helices, (c) coupled radial spirals.

The use of coupled impedance electrodes approximately increases the electric field intensity fourfold. Both relative homogeneity and increased intensity are achieved by superimposing the exponential distributions of the fields excited by the impedance electrodes.

#### PRACTICAL IMPLEMENTATION

SWS-based applicators were industrially applied at 27, 40, 915, and 2,450 MHz. A diaphragm waveguide was used for ground meat heating [7], a radial comb was used in a portable microwave oven [8], coupled meanders were used for heating food, disinfecting seeds and tubers in agriculture, fabricating wood boards, drying wood stokes, and defrosting food fat [9]. SWS-based applicators were also used for thermal processing of flat dielectric materials, for drying textiles, transfer printing, hardening concrete slabs, and surface treating semiconductors. Some proposed and realized SWS applicators are shown in Figures 2 and 3.

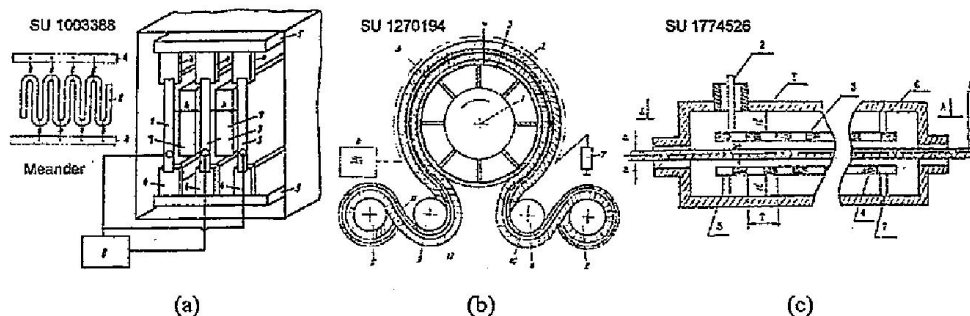


Figure 2. SWS-based units for heating (and their corresponding patent numbers): (a) RF chamber with three parallel impedance electrodes with a meander configuration, (b) transfer printing apparatus, (c) chamber with two coupled meanders.

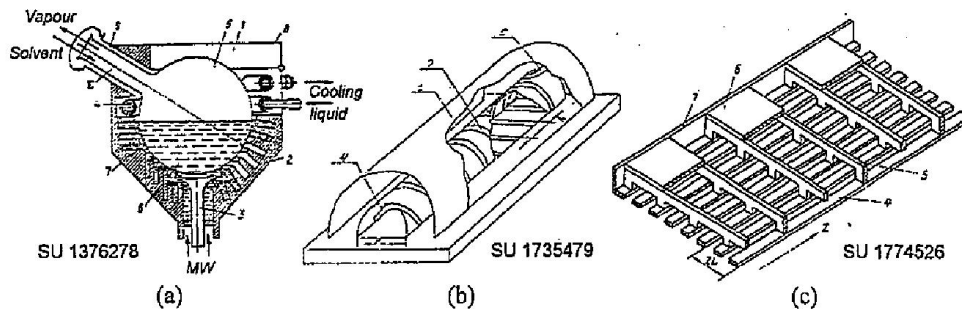


Figure 3. SWS-based heating devices with patent numbers: (a) chamber evaporating chemicals, (b) applicator for melting road coating, (c) applicator for treating flat dielectric material.

In a significant break-through, RF and MW heating was applied to medical applications using SWSs. Applicators, radiators, and coagulating scalpels were proposed and fabricated. MW radiators for internal and external therapy were approved and manufactured for clinical application.

## CONCLUSION

SWS technology is characterized by high efficiency, simplicity and flexibility. SWS-based applicators and radiators can operate in very wide frequency bands with dimensions significantly less than a wavelength in free space. They do not radiate in free space and can be used in the open volumes. This technology has been successfully used in the chemical, semiconductor, agricultural, medical and food industries.

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