I. V. Ivanov, *Low-temperature ferroelectrics: dielectric nonlinearity and parametric interactions in the microwave band.* The dielectric nonlinearity of ferroelectrics in the microwave band—the nonlinear dependence of the ionic polarization of the crystals on the strength of the external field—reflects the microscopic anharmonicity of these crystals and is usually described phenomenologically in terms of equilibrium thermodynamics.[1,2] The macroscopic characteristic of the crystals—the dielectric constant—changes on a change in the constant external field E_0, and also "tracks" the instantaneous value of the high-frequency field E if the frequency of this field is much lower than that of the soft ferroelectric mode at the particular temperature. In this case the dielectric nonlinearity can be characterized by the static and dynamic nonlinearity coefficients $\alpha_h^{st}(E_0)$ and $\alpha_h(E_0)$:

$$\varepsilon(E_0+\Delta E_0) = \varepsilon(E_0)[1+\alpha_1^{st}\Delta E_0+\alpha_2^{st}(\Delta E_0)^2+\ldots], \quad (1)$$

$$\varepsilon(E_0+E) = \varepsilon(E_0)[1+\alpha_1 E+\alpha_2 E^2+\ldots], \quad (2)$$

where $\varepsilon(E_0)$ is the low-signal ($E \to 0$) dielectric permittivity at the given displacement field E_0. The macroscopic and microscopic[3] approaches to description of ferroelectric phenomena are based on postulation of expansions of either the thermodynamic potential or the system Hamiltonian in series, the coefficients of which can as yet be obtained only from experiment. Any experiment to study the linear dielectric parameters of ferroelectric crystals under conditions of a varying displacement field is suitable for determination of the static nonlinearity coefficients in (1). The frequency-multiplication effect[4] can be used to determine the coefficients of dynamic nonlinearity in (2). Measurement of frequency-doubling efficiency permits determination of $\alpha_1 = (1/\varepsilon)d\varepsilon/dE$—the coefficient that characterizes the quadratic nonlinearity, which is most important in applications.

Nonlinear interactions between waves of different nature in solids are widely used in devices operating in widely scattered frequency ranges—from audiofrequency to optical. If we consider only the interactions of electromagnetic waves in nonlinear crystalline media and only those media in which these interactions can be effective in practical applications, it must be acknowledged that the range of crystals now known are promising for applications to the microwave band is extremely limited. It consists of strontium titanate and potassium tantalate crystals, which have high dynamic nonlinearity and low losses in the microwave band.

$SrTiO_3$ and $KTaO_3$ crystals are low-temperature virtual ferroelectrics in the sense that their phonon spectra have soft polar modes the frequencies of which for the zeroth wave vector decreases sharply as the temperature decreases and approaches absolute zero. At $T=4.2$ K, these frequencies are 15 and 20 cm^{-1} for $SrTiO_3$ and $KTaO_3$, respectively. The dielectric permittivity of these crystals and the dielectric nonlinearity also increase accordingly with decreasing temperature. Figure 1 shows temperature curves of dielectric permittivity and dynamic nonlinearity for strontium titanate and potassium tantalate crystals, as measured at a frequency of $0.5\cdot10^9$ Hz. The data on the $\alpha_1(T)$ dependence were obtained in an experiment with doubling of the frequency from 0.5 to 1.0 GHz and correspond to the displacement-field value at which α_1 reaches its maximum at $T=4.2$ K. For $SiTrO_3$, the displacement field $E_0(\alpha_1^{max})$ is of the order of 0.2 kV/cm, and for $KTaO_3$ it is an order of magnitude larger.

The effectiveness of the nonlinear interactions is determined not only by the dynamic nonlinearity of the crystals, but also by their dielectric-loss levels. Apart from losses of fundamental nature—the phonon losses, which necessarily decrease on deep cooling of the crystals due to the decrease in the populations of the corresponding phonon modes, nonlinear ferroelectric crystals are also subject to other multiple dielectric-loss mechanisms. Figure 2 shows plots of the dielectric loss tangent against temperature for $SrTiO_3$ and $KTaO_3$ crystals from measurements at a frequency of the order

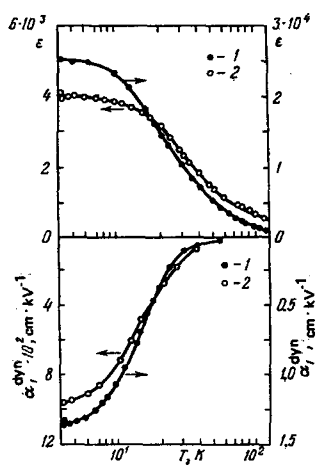

FIG. 1. Temperature curves of dielectric permittivity (left) and coefficient of dynamic nonlinearity (right) of strontium titanate and potassium tantalate crystals. 1—strontium titanate; 2—potassium tantalate.

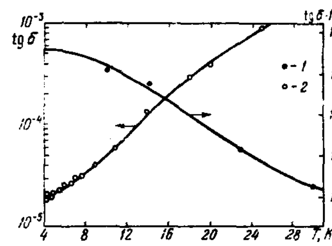

FIG. 2. Temperature dependence of dielectric loss tangents of strontium titanate (1) and potassium tantalate (2) crystals at 10 GHz.

of magnitude of 10^{10} Hz. The sharply different variations of tanδ with temperature for strontium titanate and potassium tantalate—crystals that are similar in structure and many physical properties—are to all appearances a result of the fact that strontium titanate undergoes a nonferroelectric structural phase transition at about 110 K, while potassium tantalate retains the same cubic structure at all temperatures and, like strontium titanate, "prepares itself" for a ferroelectric phase transition as $T\to0$ K. Below 110 K, strontium titanate crystals break up into structural domains with mechanically stressed boundaries between them. Scattering of phonons and additional energy dissipation are possible on these boundaries. Attention is drawn to the exceptionally low loss level in potassium tantalate and the tendency for the losses to decrease further on cooling below 4.2 K.[5] This makes potassium tantalate, which possesses high nonlinearity (see Fig. 1), highly promising as a basis for the design of practically efficient nonlinear microwave devices, and parametric amplifiers in particular.

Distributed dielectric resonators, and nonlinear types among the possible variations, are the most expedient structures for these nonlinear devices.[6,7] An example might be a transmission-line segment filled with a ferroelectric. Lines with transverse electromagnetic fields (of the TEM type) have been the simplest ones for design and experimental work. A calculation made for such a line segment, excited by a strong pump source at the kth harmonic frequency, for the case of excitation of vibrations in the line at the frequencies of two other harmonics ($\omega_m, \omega_n; \omega_k=\omega_m+\omega_n$) gives the following simple relation for the threshold of parametric amplification (power gain $G=1$):

$$u_{sg}^{thr} = \frac{4\,\mathrm{tg}\,\delta l}{\alpha}\sqrt{\frac{\omega_m}{\omega_n}}, \tag{3}$$

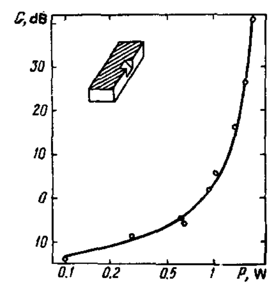

FIG. 3. Power gain vs pump power for parametric amplifier using strontium titanate crystal resonator.

where u_{sg} is the amplitude of the standing pump-voltage wave in a segment of length l open at both ends; $u_k = u_{sg} \cos(k\pi x/l)$ and $\tan\delta_l$ is the effective value of the resonator's loss tangent (Fig. 2) when it has an intrinsic figure of merit $Q_0 = 1/\tan\delta_l$. When $u_{sg} = u_{sg}^{thr}(1+\beta)$, where β is the coupling coefficient of the resonator and the external circuits, spontaneous excitation begins in the system ($G \to \infty$). Figure 3 is a plot of the gain against pump power.[8] These data were obtained on an amplifier in the form of a single-crystal $SrTiO_3$ plate that was metallized at both ends. The amplifier was operated in a quasidegenerate mode ($\omega_k = 2\omega_m = 2\omega_n$); the signal frequency $\omega_s \approx \omega_m$ with pulsed pumping. This last circumstance was a result of the relatively high losses in the metallized resonator. With "transparent" electrodes that are not as thick as the skin layer, it is possible to minimize the effect on the Q-factor, which is determined only by the losses in the dielectric, and since the pump power required for a given gain is proportional to the cube of the loss tangent, the amplifier is enabled to work with a continuous pump with a field strength small enough so that equilibrium conditions in the medium are not disturbed. In this case the level of the amplifier's intrinsic noise will be determined only by the equilibrium thermal processes in the lattice of the dielectric from which the deep-cooled resonator is made. The usual parametric-amplifier calculation shows that the effective noise temperature of an amplifier operating in a degenerate regime at high gain ($G \gg 1$) will tend to the value $T_N \to T_0/2\beta$, i.e., will amount to a few degrees K on cooling to liquid-helium temperatures. This low noise temperature makes it possible to compare the low-temperature-ferroelectric amplifier with the cavity-type maser. Another possible variant is, of course, the traveling-wave amplifier, the effective noise temperature of which would tend to $T_N \to (T_0/2) + T_n$ at high distributed gains, where, as above, T_0 is the temperature of the dielectric, and T_n is the temperature of the matched line load at the combination frequency. The absence of the requirement of a strong stable magnetic field, their immunity from overloading at the input all the way up to signal levels in excess of the pump level, possible low sensitivity to pump-power variation, and high radiation stability—all these properties of low-temperature-ferroelectric parametric amplifiers make them highly promising devices.

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