Modeling of Nonlinear Effects in HTSC Filters

A.I. Luchaninov, D.S. Gavva, E.V. Krykun, J.V. Vishniakova

Abstract – **currently HTSC microwave devices (resonators, filters, etc.) have found a wide application in various radioelectronic systems. Detailed investigations into HTSC have shown that its surface impedance shows nonlinear characteristics. The work examines nonlinear effects in microstrip HTSC filters. Results of investigation into such devices are presented.**

Keywords – **HTSC filter, nonlinear surface impedance, NIE, filter selectivity.**

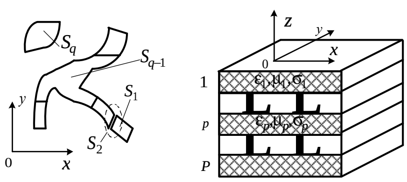
I. INTRODUCTION

A number of works are devoted to the investigation into nonlinear electrodynamic devices. Analysis of nonlinear effects in microwave HTSC devices attracts a particular interest. More detailed investigations into HTSC have shown that its surface impedance shows nonlinear properties. This means that devices applying the superconductivity effect are nonlinear ones. The analysis [1] shows that nonlinear effects in the HTSC structures can cast doubt on the advisability of HTSC materials utilization in the microwave devices. In this connection the analysis of emerging nonlinear effects is required at the stage of the device design.

The given work presents the investigation results of the effects in the HTSC filters.

II. MATHEMATICAL MODEL OF HTSC FILTERS

When constructing the mathematical model (MM) it was supposed that in the general case a HTSC filter is a microstrip structure (MSS) formed by a set of Q conductors S_q. Conductors are placed on the boundaries of a multilayer flat-layered medium, whose the p-th layer material parameters are e_p, m_p, s_p, the total number of layers is P (Fig. 1).



a) b)

Fig.1 To the microstrip filters design problem statement

The following nonlinear boundary conditions are satisfied on the conductor surface S_q of the MSS:

$$\mathbf{n}(\mathbf{r})\times\mathbf{E}(\mathbf{r},t)=\mathbf{n}\times\hat{\mathbf{Z}}_q[\mathbf{r},\mathbf{j}(\mathbf{r},t)]\Big|_{S_q}, \qquad (1)$$

where: $\mathbf{n}(\mathbf{r})$ is the outer conductor S_q surface normal at the point **r**; $\mathbf{E}(\mathbf{r},t)$ is the tangential component of the electric field intensity; $\hat{\mathbf{Z}}_q[\cdot]$ is the nonlinear operator describing conductor S_q surface impedance properties at the point **r**; $\mathbf{j}(\mathbf{r},t)$ is the surface current density on S_q.

The particular form of the operator $\hat{\mathbf{Z}}_q[\cdot]$, and, consequently, (1) depends on the conductor S_q properties. If S_q is a perfect conductor, (1) takes the form:

$$\mathbf{n}(\mathbf{r})\times\mathbf{E}(\mathbf{r},t)\Big|_S=0; \qquad (2)$$

if Leontovich boundary conditions are satisfied on the conductor's boundary, then:

$$\mathbf{n}(\mathbf{r})\times\mathbf{E}(\mathbf{r},t)=\frac{1}{\sqrt{2p}}\int_{-\infty}^{\infty}Z_s(\mathbf{r},w)[\mathbf{n}(\mathbf{r})\times\mathbf{J}(\mathbf{r},w)]\exp(jwt)dw\Big|_S, \qquad (3)$$

where $Z_s(\mathbf{r},w)$ is the surface conductor impedance at the point $\mathbf{r}$ at the frequency w; $\mathbf{J}(\mathbf{r},w)$ is the complex amplitude of the surface current density at the frequency w. If S_q is a high-temperature superconductor, it is supposed [2] that

$$\mathbf{E}(\mathbf{r},t)\approx a_{NL}(j(\mathbf{r},t))\mathbf{j}(\mathbf{r},t)+\frac{d}{dt}\big(b_{NL}(j(\mathbf{r},t))\mathbf{j}(\mathbf{r},t)\big), \qquad (4)$$

where: $a_{NL}(j(\mathbf{r},t))$ and $b_{NL}(j(\mathbf{r},t))$ are the functions describing nonlinear properties of the HTSC conductor.

Inclusion of the linear and nonlinear lumped elements in the MSS was also provided. As an example in Fig. 1,a a gap region S_2 for a two-pole lumped element inclusion is indicated by a dotted line. In this case it is supposed that S_2 is a narrow slot of Δ width and in the region S_2 the following condition is satisfied:

$$\mathbf{E}(\mathbf{r},t)=\frac{1}{\Delta\cdot j}\mathrm{F}_k[Wj(\mathbf{r},t)]\mathbf{j}(\mathbf{r},t), \qquad (5)$$

where: W is the width of the conductor in which a lumped element is inserted, $\mathrm{F}_k[\cdot]$ is the volt-ampere characteristic of a lumped element.

The system of nonlinear integral equations (NIE) was derived for such MSS in the following form with respect to the surface current density frequency components distribution:

$$\mathbf{n}_p\times\iint_S\overset{\leftrightarrow}{G}_i\left(\mathbf{r}_p,\mathbf{r}'_q\right)\mathbf{J}\left(\mathbf{r}'_q,n_i\right)d\left|\mathbf{r}'_q\right|-$$

$$\Im_i\left\{\mathbf{n}_p\times\hat{\mathbf{Z}}_{S_q}\left[\mathbf{r}_p,\sum_{n=-N}^{N}d_n\mathbf{J}\left(\mathbf{r}_p,\nu_n\right)e^{jn_nt}\right]\right\}=$$

$$=\begin{cases}\mathbf{n}_p\times\mathbf{E}^{\mathrm{ext}}\left(\mathbf{r}_p,w_k\right), & when\quad n_i=w_k\\ 0, & when\quad n_i\neq w_k\end{cases}\qquad\forall\; i=\overline{0,N}. \qquad (6)$$

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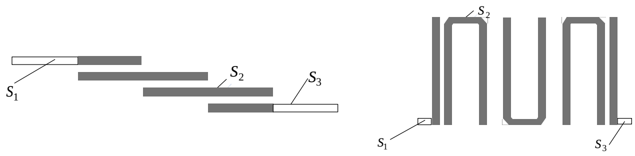
Here: $\overset{\leftrightarrow}{G}_i\left(\mathbf{r}_p,\mathbf{r}_q^{'}\right)$ is the tensor Green function of the flat-layered medium (Fig. 1,b); $\mathbf{r}_p,\mathbf{r}_q^{'}$ are the observation and integration points respectively; $\mathbf{E}^{\text{ext}}\left(\mathbf{r},w_k\right)$, $\mathbf{J}\left(\mathbf{r},n_n\right)$, are the complex amplitudes of the external electric field intensity and surface current density at the frequency v_n; $\Im_i\{\cdot\}$ is the Fourier transform operator. Integration in (6) is carried out over the surface $S=\bigcup_{q=1}^{Q}S_q$ of all elements of the structure.

This system describes the filter response (the surface current distribution) at the frequencies $n_n = m_{0n}w_0 + m_{1n}w_1 + ... + m_{Kn}w_K$ ($m_{in} = 0,\pm 1,\pm 2,...$), being excited by the external sources $\mathbf{E}^{\text{ext}}(\mathbf{r},w_k)$ at different frequencies w_k, ($k=\overline{0,K}$, K+1 is the total number of various external signal frequencies).

The method of moments with various systems of basis functions for linear and nonlinear operators was used for the numerical solution of the NIE.

III. Investigation Results

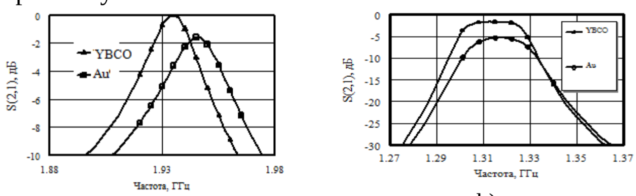
Results of the filter characteristics investigation are presented. Fig. 2 shows the sketches of the filters under investigation. It is assumed that the filter S_2 is the HTSC, and the feeding lines S_1 and S_3 are perfect conductors.



a) b)

Fig.2 Sketches of a) the end-coupled filter and b) the hairpin-line filter

Investigation results of the resonance characteristics for the given filters made using gold (conductivity 4.10x10^7 S) and superconductor are shown in Fig. 3,a and 3,b, respectively.



a) b)

Fig.3 AFC of a) the end-coupled filter and b) the hairpin-line filter at a low input power level ($P_{\text{in}} = -30$ dBm)

It can be seen from Fig. 3 that in the pass band the HTSC filter losses are considerably lower than the losses of the filter made of gold. Therefore the primary consideration was given to the nonlinear properties of the HTSC filters.

Fig. 4 and 5 show the HTSC filters AFC for various input power levels. It can be seen that the AFC behavior is identical to the disk resonator AFC behavior [3]. The difference consists in that the distortion degree of the filters' AFC is slightly lower than the single resonator AFC distortion [3].

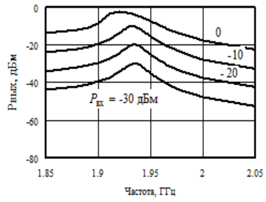


Fig.4 AFC of the HTSC end-coupled filter at various input power levels

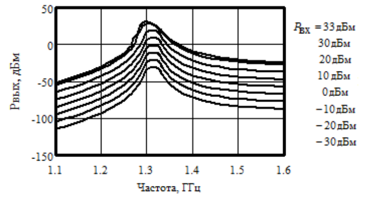


Fig.5 AFC of the HTSC hairpin-line filter at various input power levels

Fig. 6 and 7 show dependences of the output power of the first and third harmonics of the filters on the input power. It follows from the comparison of the given dependences that nonlinear distortions of the hairpin-line filter are considerably lower than those of the end-coupled filter, which in turn are lower than distortions of the resonator.

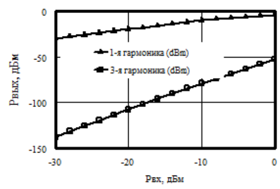


Fig.6 Dependence of the output power of the first and third harmonics of the end-coupled filter on the input power

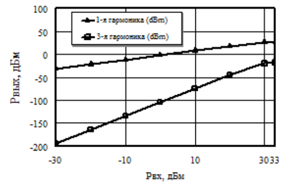


Fig.7 Dependence of the output power of the first and third harmonics of the hairpin-line filter on the input power

Considering that the hairpin-line filter selectivity is higher than that of the end-coupled filter and higher than the resonator selectivity [3], it can be stated that the selective properties of the microwave device are directly associated with its nonlinear properties.

IV. Conclusion

In this way the results presented in the given work for the HTSC filters have shown that nonlinear surface impedance results in the resonant frequency shift of the device with the input power growth. This in turn results in different levels of intermodulation distortions and upper harmonics levels at different pass band edges.

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