Changing and control of harmonic generation in superconducting films

S.S. Tinchev
Institute of Electronics, Bulgarian Academy of Sciences, Sofia 1784, Bulgaria
stinchev@ie.bas.bg

Abstract. The generation of high-order harmonics from ion implanted YBCO films has been investigated by monitoring of its response to an alternating magnetic field. These harmonics are generated because of the high nonlinearity caused by sudden magnetic flux penetration above the first critical field. Harmonics up to 100th order and interference effects were observed.

1. Introduction
Harmonic generation is very important phenomena in the electronics, because it is a base for operation of many electronic devices such as frequency multipliers, upconverters and mixers. Harmonic generation is a nonlinear process in which rich harmonic content appears in the oscillating electromagnetic field because of the nonlinear properties of the exposed material. In order this process to be efficient, high nonlinearity is needed. Usually the nonlinearity of the exposed material is low, therefore only harmonics with low numbers are generated even at high amplitudes of the exciting field. There are, however, some materials and processes, where high order harmonics are generated. For example in thin gases irradiated with short laser pulses high optical harmonics were observed up to 300th [1]. Such high order harmonic generation is caused by the extremely high nonlinearity of the material and the high excitation field.

Superconducting materials possess also high nonlinearity. Already 1988 – 1989 many interesting electrodynamical properties of the high-Tc materials were observed determined by this high nonlinearity, including generation of harmonics with numbers up to 40th. These observations were made on bulk and powder materials [2]. Later when the work in the high-Tc was shifted to thin films, investigation of harmonic generation was carried out mainly as a powerful tool for measurement of critical temperature or critical current density of thin films by monitoring its 3th harmonic [3].

2. Origin of the high-harmonic generation in superconductors
Many models were introduced to explain the harmonic generation in superconductors. The most popular one is probably the critical state model [4] suggested by Bean already 1964 to explain the magnetization of type II superconductors. In the loop model [5] the high-Tc superconductor is regarded as a granular material with many superconducting loops interrupted by weak links. There are also other theoretical models [6], but they do not explain satisfactorily why the superconductors generate harmonics with high order. The origin of this generation is, however, very similar to the process of high optical harmonic generation. It is a cooperative phenomenon that involves many single
processes, which happen almost simultaneously. In the case of superconductivity these processes are penetrations of the magnetic flux in the superconductors in form of many single flux lines – Abrikosov vortices. This penetration starts at the first critical magnetic field $H_{c1}$ and occurs very sudden. The results is a high nonlinearity of the material response. Actually this is the origin of the high order harmonic generation. In the B-H diagram (Figure 1) of type II superconductors this is manifested as derivative $\frac{dB}{dH} \to \infty$ at the point $H = H_{c1}$, generating series of voltage spikes in time. (Figure 2).

For oscillating fields, however, the process is more complicated because hysteretic loops are described. This fact does not change significantly the above-described picture, because most of the time during the AC period, the magnetic field is changed slowly. Only at $H = H_{c1}$ series of voltage spikes arise. Fourier transformation of these series gives odd harmonics in the frequency space:

$$ F(\omega t) = \frac{4A}{\pi} \left( \cos \theta \sin \omega t + \frac{\cos 3\theta}{3} \sin 3\omega t + \frac{\cos 5\theta}{5} \sin 5\omega t + \ldots \right) $$ (1)

Here $A$ is the amplitude of the pulses and $\theta$ is the angle of cut-off.
3. Control of harmonic generation

Obviously if one can find how to influence the first critical field $H_{c1}$ it will be possible to change the process of harmonic generation. Ion modification/implantation is such a process. It is well known that by choosing the proper kind of ions, their energy and doses, it is possible to control practically all parameters of a superconducting film, including $H_{c1}$. In the practice it is desirable to change only one harmonic or at least a group of harmonics. This is, however, not possible simple by variation of $H_{c1}$. It can be done if we use two samples driven by the same magnetic field and then let the generated coherent harmonics add (or subtract) by an interference. This idea can be realized in one sample only implanting a part of the same film.

4. Experiment

$YBa_2Cu_3O_{7-\delta}$ films with thickness 200-300 nm were used in the experiments. One half of the samples was implanted with oxygen ions at 100 keV and dose $2 \times 10^{13}$ O$^+/\text{cm}^2$. As a result the critical temperature of the implanted part was reduced to 82-83 K, while the $T_c$ of the virgin films was 90 K. At 77 K (the operation temperature) both parts of the films were in the superconducting state.

In the nonimplanted samples we observed usual spectra – harmonic intensity decreases continuously with increasing harmonic number (Figure 4). The drive frequency is 1 kHz. In the samples, where one half of the film was with reduced parameters because of the ion modification many minima and maxima were passed with increasing harmonic number – Figure 5. To our opinion this is a clear interference of the harmonics generated from both parts of the films.
Further we should point out that the positions of the extremums depend on the amplitude of the oscillating magnetic field. It can be seen in Fig. 5 that with increasing amplitude of $H_{\text{AC}}$ they are shifted to the left. For example, position of the first maximum is changed from 13th, to 25th harmonic. In this way choosing proper $H_{\text{AC}}$ amplitude it is possible to enhance or depress certain harmonic, or at least a group of neighbor harmonics.

5. Conclusions
The high order harmonic generation in high-$T_c$ superconducting films were explained as a result of the sudden penetration of magnetic flux vortices if the first critical field $H_{\text{c1}}$ was exceeded, which causes series of voltage spikes of the magnetic flux in time. Their Fourier transformation gives a comb of odd harmonics. We found that the harmonic generation can be influenced by the ion implantation of the samples. In homogeneous samples the amplitudes of the high harmonics decrease monotonically with its number. In inhomogeneous samples we observe up to 100th harmonics and interference effects. We hope that these results can be used in superconducting electronics.

References
[1] Bartels R, Backus S, Zeek E, Misoguti L, Vdovin G, Christov I P, Murnane M M, Kapteyn H C 2000 Nature 406 164
[2] Lam Q H, Jeffries C D, Berdahl P, Russo R E and Reade R P 1992 Phys Rev B 46 437
[3] Claassen J H, Reeves M E, Soulen R J 1991 Rev. Sci. Instrum. 62 996
[4] Bean C P 1964 Rev. Mod. Phys. 36 31-39
[5] Lam Q H, Jeffries C D, Phys. Rev. B 39, 4772
[6] Anderson P W and Kim Y B Rev. Mod. Phys. 36, 39

Figure 5. Harmonic spectra generated by the YBCO thin film half implanted with 100 keV, $2 \times 10^{13}$ O$/cm^2$. 

Further we should point out that the positions of the extremums depend on the amplitude of the oscillating magnetic field. It can be seen in Fig. 5 that with increasing amplitude of $H_{\text{AC}}$ they are shifted to the left. For example, position of the first maximum is changed from 13th, to 25th harmonic. In this way choosing proper $H_{\text{AC}}$ amplitude it is possible to enhance or depress certain harmonic, or at least a group of neighbor harmonics.