Temperature Dependence of Microwave Properties of HTS Multipole Lowpass Filters Consisting of Microstrip Open-Stub Lines

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CONTENTS

ABSTRACT

Using high quality high-T_c superconducting (HTS) YBCO thin films, we designed and fabricated 3-pole, 5-pole, and 7-pole lowpass filters consisting of microstrip transmission lines and open-stub lines. We measured the microwave response of the filters in the temperature range of T=85 K to 27 K. At $T = 30$ K, the observed inband insertion loss was 0.14 dB and 0.02 dB for the 5-pole and 7-pole filters, respectively. The cut-off frequency was 4.7 GHz for the 5-pole filter and 7.9 GHz for the 7-pole filter. To the authors' knowledge, the measured inband insertion losses are the best values reported so far for the open-stub line type HTS multipole lowpass filters. The skirt property of the 5-pole filter showed a large improvement over that of the 3-pole filter as predicted from the simulation. We found that, to obtain a stable performance, the HTS multipole lowpass filters should be operated at the temperatures between 60% and 70% of T_c.

I. INTRODUCTION

Microwave passive devices fabricated using high-T_c superconducting (HTS) thin films have been paid a great deal of attention for possible applications in microwave communications. HTS materials have been considered good for practical microwave applications because of their excellent microwave properties of low microwave surface resistance R_s and stable electric conductivity over a wide range of microwave frequencies [1]. The recent development of deposition techniques such as pulsed laser deposition [2] and sputtering [3] added technical ground for easy fabrication of high quality HTS thin films that are essential for the realization of superconductor devices. Because of the advantages of high microwave performances and small size, HTS devices are expected to replace conventional microwave circuits fabricated with either copper or gold in the near future. In accordance with the current development in mobile telecommunications and satellite communications which use ultra-high frequencies up to 10 GHz range, the imminent development of high performance HTS microwave devices is in great demand. Provided that uniform and high quality HTS epitaxial thin films as large as 3" in diameter are prepared [3], the integration of filters, oscillators and mixers would be possible in the form either of purely HTS devices or of hybridization with conventional high-speed GaAs devices [4].

So far, many authors have reported that HTS microwave devices offered superior performance to those of conventional devices made of copper [5]-[7]. If a filter consisting of microstrip transmission lines is fabricated with copper on an alumina substrate, the insertion loss in the passband is known to increase with a number of poles [8]. By contrast, an HTS filter of the same design does not show any significant sacrifice in the inband insertion loss with a large number of poles. This result is achieved because of the low surface resistance and the high quality factor of HTS thin films. Thus, using HTS materials for filters with a large number of poles is advantageous for achieving good filter characteristics such as low inband insertion loss and sharp skirts. While an optimized copper filter typically showed the inband insertion loss of about 2 dB at $T = 77$ K [9], HTS filters exhibited a significant enhancement to about 0.5 dB [5]-[7].

For the study of the microwave performance of HTS element devices, we designed multipole (3-pole, 5-pole, and 7-pole) lowpass filters with microstrip transmission lines and open-stub lines according to microwave circuit theory [10]. Until now, many papers on HTS filters [5]-[7], [11], [12] have studied their microwave properties at liquid nitrogen temperatures or only at certain temperatures without knowing their behavior over a wide temperature range. In the practical point of view, it is important to know how the device characteristics of HTS filters vary with temperature below $T = 77$ K. In this study, we report the growth and characterization of HTS thin films and the design and fabrication of multipole lowpass filters. We also present the results of microwave response of HTS multipole lowpass filters as the temperature is varied from $T = 85$ K to 27 K.

II. GROWTH OF $YBa_2Cu_3O_{7-x}$ FILMS AND THEIR STRUCTURES

Using *in situ* pulsed laser deposition (PLD), we prepared high-temperature superconducting $YBa_2Cu_3O_{7-x}$ (YBCO) thin films on MgO (100) substrates. Fig. 1 is a schematic drawing of the PLD system. We used a XeCl excimer laser that produced a laser beam with a wavelength of 308 nm, a pulse repetition rate of 5 Hz, and a pulse duration of 14 ns. Energy fluence at the target surface was about 1 J/cm^2. The growth rate was approximately 0.1 nm/pulse. Target material was a 99.999% high purity YBCO pellet of one inch diameter. The base pressure of our chamber was about 1×10^{-5} Torr. Deposition was done in an oxygen atmosphere of 200 mTorr. Substrates were silver-pasted on the surface of a SiC heater for heating and annealing. The growth temperature was about 750 °C, and annealing was done at 550 °C for 30 min. The typical film thickness was about 300 nm as measured with an α-step profilometer.

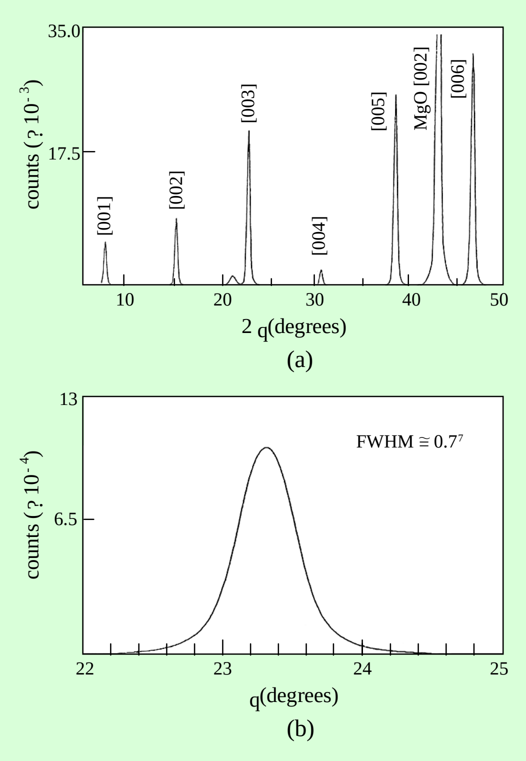

Fig. 1. X-ray diffractograms: (a) high angle θ-2θ diffraction geometry and (b) rocking curve geometry about the [005] peak.

Structural analysis and electrodynamic measurements on the films proved high quality epitaxial growth of HTS YBCO on MgO substrates, though there was as large a lattice mismatch as 9 %. Fig. 2 is a typical x-ray diffractogram of the films (a) in the Bragg-Brentano geometry and (b) in the rocking curve measurements. The θ-2θ x-ray diffraction revealed that the films had grown preferentially along the c-axis parallel to the normal of a substrate as evidenced with well-defined $[00\ell]$ diffraction peaks. X-ray rocking curve measurements about the [005] peak showed a full width at half maximum (FWHM) of 0.7 degrees. The results imply that the films have a strong film texture in the *c*-axis and their mosaic spread of crystallites is as small as that of a YBCO single crystal. In the cross-sectional TEM micrographs, the observation of *a*-*b* planes para-llel to a substrate was complementary to the x-ray diffraction measurements for the growth of layered structure along the *c*-axis direction [5]. The film surface looked mirror-like smooth, but the microscopic topology from Atomic Force Microscopy (AFM) images appeared rough because of many boulders and pin holes generated during the laser ablation process. In addition, we measured the electrodynamic properties of films by using a standard four probe method. Fig. 3 is a typical plot of resistivity *vs.* temperature. The observed critical temperature, T_c, was about 85 K. The YBCO films showed a metallic behavior in that the resistivity decreased linearly as for $T \geq T_c$, and extrapolated approximately to zero at T=0 K.

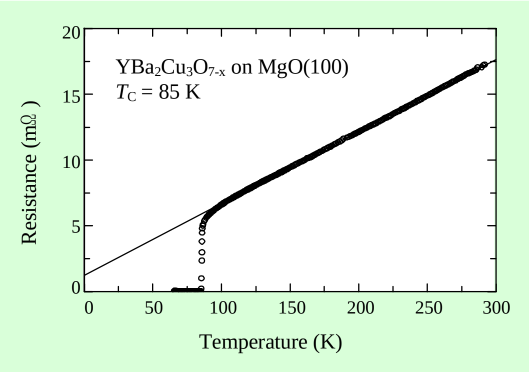

Fig. 2. Resistance *vs.* Temperature at T_c = 85 K.

III. DESIGN OF MICROWAVE MULTIPOLE LOWPASS FILTERS

We designed Tchebyshev lowpass filters (LPFs) that are of particularly good for the clear definition of passband and sharp skirts [10]. For effective design, we used the insertion loss method (or the network synthesis method) [10] in which the amplitude and phase of an electromagnetic signal were mani-pulated easily both in the passband and in the stopband. To begin with, the circuit elements of a filter were determined in a two-port network in such a way that the ratio of power loss of transmission to insertion (or the insertion loss, S_{21}) and the ripple of insertion loss in the passband were minimized. Thus, we obtained the primary values of inductance, impedance, and capacitance of the prototype filter. By frequency transformation and impedance leveling, the device parameters were reevaluated for those of lumped elements, and then they were used to construct an LPF of lumped elements.

It is well known that an LPF of lumped elements is ineffective for high-performance microwave application because of (a) a limited range of operation frequency, (b) the lack of fine lumped elements in the market, and (c) a wide inter-distance between elements. Such disadvantages in the lumped-element LPF can be resolved easily if the device is constructed with distributed elements of microstrip transmission line. The circuit elements of fine inductance or capacitance can be realized with the segments of transmission line. Hence, we reconstructed the LPF with distributed elements of transmission line so that we could enhance its microwave performance without losing any other characteristics of a device.

The propagation of an electromagnetic wave through the LPF composed of the distributed elements would generate high order harmonics. To get rid of the high order harmonics, coupling microstrip open-stub lines to the microstrip transmission lines is very effective. The open-stub lines work like capacitors with specific capacitance values. If an open-stub line is set to $\lambda/8$ of a harmonic frequency, the harmonic component can be suppressed without damaging the passband and the cut-off frequency of LPF. The use of multiple open-stub lines for a harmonic frequency is good for further improving the frequency response of the filter [10].

In this study, we designed multipole (3-pole, 5-pole, and 7-pole) lowpass filters with microstrip open-stub lines according to the microwave circuit theory of transmission lines [10]. Their theoretical microwave responses were optimized with computer simulation by using a commercial tool (Supercompact^{TM}). In the simulation, we used a dielectric constant of 9.88 for MgO substrates [13], and we assumed that the microstrip lines had infinite conductivity (a perfect conductor). In Fig. 5, the dashed lines indicate the results of simulation on the frequency responses of multipole LPFs. Inset in each graph is a corresponding lowpass filter pattern. The designed cut-off frequencies are 5.0 GHz, 5.0 GHz, and 8.0 GHz for 3-pole, 5-pole, and 7-pole filters, respectively. Device patterns fit substrate sizes of 10 mm × 10 mm × 0.5 mm, 15 mm × 15 mm × 0.5 mm, and 20 mm × 20 mm × 0.5 mm, respectively.

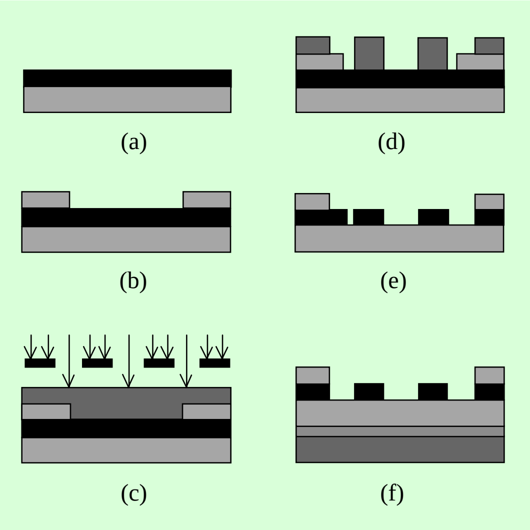

Fig. 3. Procedure of device patterning: (a) YBCO/MgO(100), (b) Au/Ti on (a), (c) UV exposure through Cr-mask onto a photoresist layer, (d) developed photoresist (PR) device pattern, (e) EDTA etched pattern, and (f) a completed device with a ground plane.

IV. FABRICATION OF HTS LOWPASS FILTERS

We patterned HTS lowpass filters by using both a standard photolithographic process and a wet etching technique.

Fig. 4 shows a procedure used for fabricating the lowpass filters. Before etching, we deposited an extra bilayer of Au(300 nm)/Ti(1.0 nm) on YBCO/MgO at the edges where the K-connectors would be contacted (Fig. 4(b)). A film of (Au/Ti)/YBCO was covered with a photoresist (AZ5214E) 1.4 μm thick. The photoresist (PR) layer was exposed to UV radiation through a Cr-mask for 35 seconds, and then it was developed with AZ500MIF solution to get a PR device pattern (Fig. 4(d)). The Au/Ti bilayer at the contact edges was etched in a single process using an iodine-based gold etchant. Gold etching was terminated at a TiO_2 layer formed from the reaction of Ti with oxygen. The gold etching appeared not to damage the underlying YBCO layer. Then, the YBCO layer was etched out by using saturated Ethylene-Diamine-Tetra Acid (EDTA) aqueous solution (Fig. 4(e)). To complete the fabrication, we prepared Ag(2 μm)/Ti(10 nm) thin films to form a ground plane on the back side of the MgO substrate using thermal evaporation and e-beam evaporation, respectively (Fig. 4(f)).

V. RESULTS OF MICROWAVE MEASUREMENTS AND DISCUSSION

Before the measurements, we placed a filter into a 3-component test-jig. The test-jig consisted of a base plate for both electrical grounding and thermal contact, a housing of side walls where input and output K-connectors were embedded, and a lid completing a cavity. It was constructed in a cut-off waveguide structure such that direct microwave coupling between the input (or output) K-connectors and the microstrip lines of a filter was avoided. The microwave contact between the connectors and the filter was done via a matching network included in the device pattern. A packaged device was mechanically contacted to the cold head of a cryostat (RMS LTS-II) and was cooled below the temperature of liquid nitrogen.

Since the system calibration in the cryogenic temperature is extremely important for the microwave measurements of HTS devices, we devised an HTS YBCO microstrip transmission line with matching impedance of 50 ohms. Keeping the HTS microstrip transmission line at various cryogenic temperatures of interest, we carefully calibrated the network circuit of measurements from the K-connectors at the test-jig to the terminals of a vector network analyzer (HP8510C) in both directions of microwave signal propagation. We interfaced all the instruments with the aid of a microcomputer so that the whole measurement system was fully automated for taking data and their processing.

Fig. 5 shows plots of the amplitude attenuation at several temperatures for (a) 3-pole, (b) 5-pole, and (c) 7-pole HTS LPFs. The dashed line in each figure is a simulation result, and the inset is the corresponding filter pattern. As the temperature decreased from T_c to 77 K, the amplitude attenuation (or the insertion loss) rapidly formed a characteristic profile of a lowpass filter and for $T \leq 77$ K, it approached to that of the simulation. It was not until $T = 77$ K that complete profiles of Tchebyshev filter response of the 5-pole and 7-pole HTS lowpass filters were observed. Unlike the design, however, the 3-pole filter showed a maximally-flat-filter response over the entire range of temperature. For temperatures below 77 K, the obtained filter parameters (the passband edge, the passband ripple and the inband insertion loss) converged to those of the simulation. The skirt property of all the filters, however, did not seem to change with temperatures for $T \leq T_c$. The observed frequency responses of the HTS LPFs agreed well with the simulation.

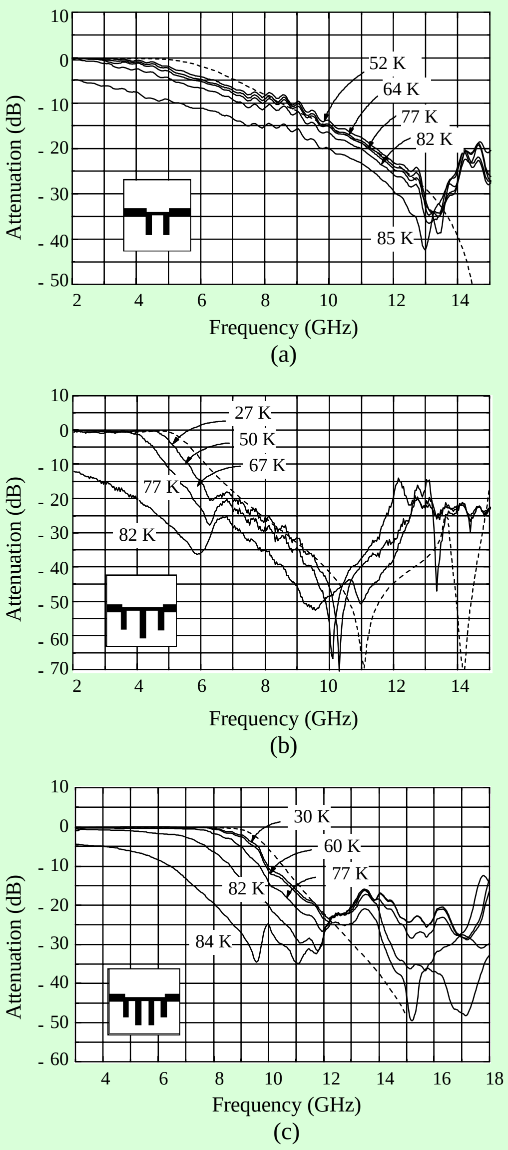

Fig. 4. Amplitude attenuation (or insertion loss) *vs.* temperature: (a) 3-pole, (b) 5-pole, and (c) 7-pole lowpass filters. Inset is a corresponding device pattern of each filter. Dashed lines are the simulated frequency responses.

Fig. 6 is a plot of the smallest inband insertion loss (or the insertion loss in the passband) *vs.* temperature for $T \leq 77$ K. The top horizontal axis in Fig. 6 represents the reduced temperature (T/T_c) with respect to the superconducting transition temperature. The open circles (solid squares) are for the 5-pole (7-pole) LPF. The dashed line marks $T = 77$ K. As the temperature decreased from $T = 77$ K, the inband insertion loss changed from 0.39 dB to 0.12 dB and from 0.28 dB to 0.02 dB for the 5-pole and the 7-pole filters, respectively. The measured minimum values of inband IL are 0.12 dB at 27 K, and 0.02 dB at 30 K for the 5-pole, and 7-pole filters, respectively. Unlike the 5-pole and 7-pole filters, the 3-pole filter showed a maximally flat response of amplitude attenuation as displayed in Fig. 5(a) so that reliable numerical results of filter parameters could

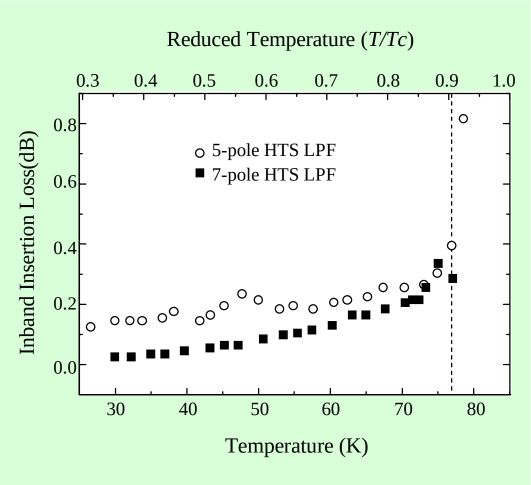

Fig. 5. Inband insertion loss (IL) *vs.* temperature (T) and reduced temperature (T/T_c) for T $\leq$ 77 K: 5-pole (○), and 7-pole (■) filters. A dashed line is at T = 77 K.

not be obtained. The measured minimum insertion loss was 0.02 dB below 50 K. To the authors' knowledge, these are the best values of inband insertion loss reported so far for open-stub line type HTS multipole lowpass filters.

The passband ripples were not noticeable for all the HTS LPFs. The peak-to-peak passband ripple was 0.7 dB for the 5-pole filter and 0.3 dB for the 7-pole filter.

Fig. 7 shows the observed cut-off frequency, f_c, as a function of temperature. We defined f_c as the equi-ripple band edge frequency. The value of f_c increased rapidly as the temperature decreased from T = 77 K and gradually saturated for $T \leq 60$ K. The satura- ted f_c values at low temperatures ($T \leq 50$ K) are 4.7 GHz, and 7.9 GHz for the 5-pole filter and the 7-pole filter, respectively.

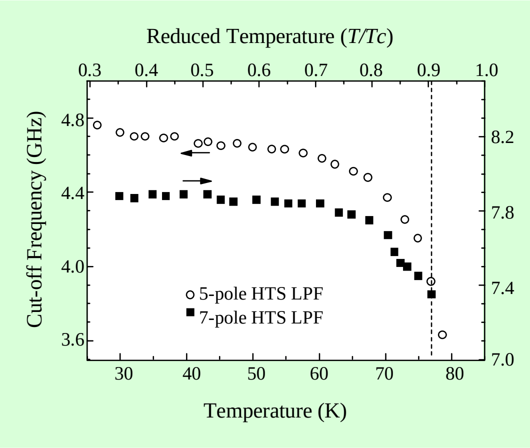

Fig. 6. Cut-off frequency, f_c *vs.* temperature (T) and reduced temperature (T/T_c): 5-pole (○), and 7-pole (■) filters. A dashed line is at T = 77 K.

Near T_c, the cut-off frequencies of the HTS LPFs exhibited a strong dependence on temperature. A similar temperature behavior was also observed in HTS microstrip resonators prepared with YBCO/MgO [13]. In [13], the authors found that the resonant frequency of the HTS microstrip line resonator increased rapidly with decreasing temperature near T_c, which was best fitted with the empirical two-fluid model. The shift of resonant frequency in an HTS microstrip resonator with temperature is mainly due to the kinetic inductance of a superconductor and the thermal expansion along its length [14]. The abrupt change of resonant frequency results from the kinetic inductance effect that dominates only at temperatures near T_c. As observed in the HTS microstrip line resonators [13], [14], we believe that the behavior of f_c with temperature of the multipole HTS LPFs resulted from the inherent kinetic inductance effect of the YBCO materials near T_c.

In Fig. 7, the f_c value of the 7-pole LPF became saturated at $T/T_c = 0.7$, earlier than that of 5-pole LPF that showed the saturation at $T/T_c = 0.6$. On the other hand, the inband insertion loss changed only a small amount, within 0.25 dB for $T \leq 77$ K. The results indicate that, for stable performance, HTS multipole filters should be operated at a temperature $0.6 \leq T/T_c \leq 0.7$.

As mentioned in section 3, one of the advantages of designing multipole Tchebyshev lowpass filters is to obtain improved skirt shaping with many poles, compared with maximally-flat-filters. Fig. 8 shows plots of amplitude attenuation *vs.* normalized frequen-cy, f/f_c. Symbols are for the measurements and lines for the simulations. Since the HTS LPFs in this work were designed to have different cut-off frequencies, we replotted their amplitude responses as a function of f/f_c, so that the skirt properties were easily compared. The skirt property of the 5-pole filter showed a large improvement over that of the 3-pole filter as expected from the simulation. By contrast, the change of the skirt property between the 5-pole and 7-pole LPFs was not significant.

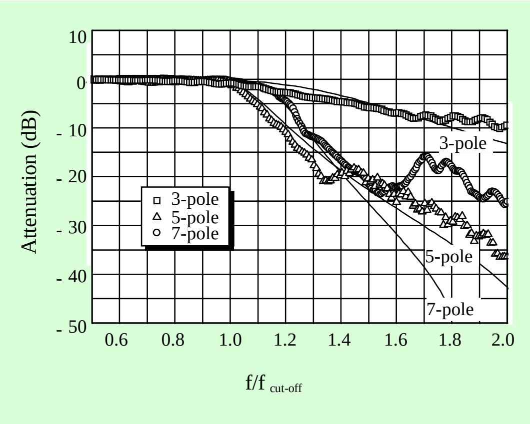

Fig. 7. Amplitude attenuation of both measurements (symbols) and simulation (line) *vs.* normalized frequency f/f_c: 3-pole (□), 5-pole (△), and 7-pole (○) filters.

VI. CONCLUSION

We prepared high quality HTS YBCO epitaxial thin films on MgO (100) substrates using *in situ* pulsed laser deposition. We designed and fabricated the 3-pole, 5-pole, and 7-pole lowpass filters consisting of microstrip line and open-stub lines. As the temperature decreased from T_c to 27 K, the amplitude response of the HTS filters varied rapidly near T_c and showed only a marginal change at lower temperatures. At $T = 30$ K, the observed inband insertion loss was 0.14 dB and 0.02 dB for the 5-pole and 7-pole filters, respectively. The cut-off frequency was 4.7 GHz for the 5-pole filter and 7.9 GHz for the 7-pole filter. A large improvement in the skirt property was observed between the 3-pole and the 5-pole filters. Our experimental results suggest that stable performance of HTS multipole filter would be obtained at temperatures between 60% and 70% of T_c.

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