HIGH - TEMPERATURE SUPERCONDUCTOR MEANDER - ANTENNA

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ABSTRACT

A novel type of an electrically small multiresonant microstrip antenna is presented. It possesses a bandpass frequency response characterized by a bandwidth which can be chosen to be relatively wide with respect to the small size of the antenna. Due to the miniaturization and especially the required narrow line - width of the strip conductors a sufficiently high radiation efficiency can only be achieved by the utilization of superconductive material.

Experimental results for a 4.2 GHz version of this multiresonant meander antenna made from the high - T_c superconductor YBCO epitaxially grown on $LaAlO_3$ with a size of $\lambda_0/10$ indicate a half - power bandwidth of 4% and a radiation efficiency of more than 60% at 77 K.

1. INTRODUCTION

Electrically small antennas are known to exhibit "very low" values of the radiation efficiency η if their linear size D is much smaller than a critical value

$$D_c = \lambda_o/(2\pi) \tag{1}$$

and if these antennas inclusive of a possible matching network (in the following considered as part of the antenna) are made from normalconducting materials [1,2]. Because of the strong influence of η onto the signal-to-noise ratio in case of low external noise [2] or for radiometric applications the utilization of high-T_c superconductors (HTS) with low losses [3] is of interest to overcome this problem. Consequently, a number of HTS antennas have been realized by different groups (see e.g. [4,5,6]) in order to demonstrate this benefit of the new material.

In order to discuss the problem of frequency bandwidth seperately from the efficiency problem, the antenna is first assumed to be (theoretically) lossless and the size D to be reduced to values smaller than the critical value D_c e. g. by decreasing the size of a dipole- or loop-antenna with matching network or by reducing D of a resonant patch antenna by means of a higher substrate permittivity or a "stepped-impedance" patch shape [6]. It is well-known that in this (theoretically) lossless case the effective area A_{eff} of the antenna remains constant although D is decreased, but the radiation quality factor Q_{rad} is governed by the inequality [9,10,11]

$$Q_{rad} \gtrsim (\lambda_o/\pi D)^3 . \tag{2}$$

For single-resonant antennas the 3 dB frequency bandwidth Δf can directly be related to Q_{rad} to be given in case of a matched load by $\Delta f/f_o \approx 2/Q_{rad}$, but this estimation is not valid in case of antennas with "closely spaced" resonance frequencies ("multiresonant antennas"). From a general investigation of the bandwidth problem [7] the maximum achievable 3 dB-bandwidth was found to be given by

$$(\Delta f/f_o)_{max} \approx 9 / Q_{rad}, \tag{3}$$

which is by a factor of about 5 higher as in the above mentioned estimation of Δf. This result agrees with the result which one obtains by combining an "optimum matching network" (Fano's theorem) [8] with an antenna of bandwidth $\Delta f/f_o = 2/Q_{rad}$. But in principle this bandwidth can also be obtained by a multiresonant antenna structure without (external) matching network.

The efficiency η is determined by Q_{rad} and the quality factor Q_{diss} describing the dissipative losses in the antenna (including a possible matching network) to be

$$\eta = 1/\left(1+Q_{rad}/Q_{diss}\right) . \tag{4}$$

This clearly shows in combination with eq.(2) that the replacement of normal conductors with superconductors is a necessary condition for the realization of a high-efficient antenna with a large degree of "miniaturization" D_c/D.

If the frequency bandwidth $\Delta f/f_o$ of an antenna is (exactly) specified by means of the particular system requirements a compact and high-efficient "bandpass-antenna" may be characterized by the following properties:

(a) Frequency response of the input reflection coefficient Γ similar to those of an bandpass filter : $|\Gamma| \lesssim |\Gamma_{max}|$ in the specified passband, but $|\Gamma| \approx 1$ in the stopband.

(b) Linear size "close" to the minimum size for the given bandwidth Δf

$$D_{min}/\lambda_o \approx \sqrt[3]{\Delta f/(90\cdot f_o)} \quad , \qquad (5)$$

which follows from eqs.(2) and (3).

(c) Efficiency η "close" to 1.

The sharpness of the "filter skirt" is in general determined by the loaded quality factor of the antenna. Therefore a high efficient HTS antenna with $Q_{rad} < Q_{diss}$ and a small size D leads according to eq. (2) to a sharp transition between the passband and the stopbands. These "bandpass antenna" offers advantages e.g. if different antenna systems for different frequencies are to be placed close to each other, because the antennas can perform a preselection function.

In the next section a particular multiresonant structure which has the above mentioned properties , namely a novel microstrip meander antenna will be presented.

2. PRINCIPLE OF MICROSTRIP MEANDER ANTENNA [12]

The basic idea of the meander antenna is illustrated in Fig. 1 by means of a strongly simplified model (transmission case):

(α) For the sake of simplicity the current distribution at the meander - structure is in a first rough approximation modeled by that of a folded but " undisturbed " microstrip transmission line section with a total length of $M \cdot L$ ($M = 5$ in Fig. 1a). Than at $f_0 = v_{ph}/2L$ a resonant current distribution exists (Fig. 1b) where the currents at all meander sections are " in phase " and therefore lead to a " constructive interfering " radiation.

At the adjacent resonance frequencies $f_{+,-} = f_0(1 \pm 1/2M)$ the current distribution (see Fig. 1c) is still in phase.

(β) In this simplified model the radiation resistance defined with respect to the maximum value of the current flowing in the meander increases according to

$$R_{rad} = v \cdot M^2 \qquad (6)$$

quadratically with the number M of meander - sections and v increases with increasing L ($< \lambda_0/2$) and substrate thickness.

(γ) M has to be chosen high enough to obtain a value of R_{rad} " close " to that of the characteristic impedance Z_c of the line. On the other hand for a wideband antenna it should be as small as possible, since according to (α) the bandwidth can be estimated to be in the order of $\Delta f \approx f_0/M$.

A more careful analysis of the meander structure shows that the simple model described above has to be modified by taking the transition to a stop - band due to the periodic structure (coupling between lines, disturbance by bends, both spatially varying with a period L) at a frequency $f_c < f_0$ into account. This effect will be refered to in the discussion of the experimental results. A description of a model which includes the transition to the stopband has because of space - limitation be omitted in this paper.

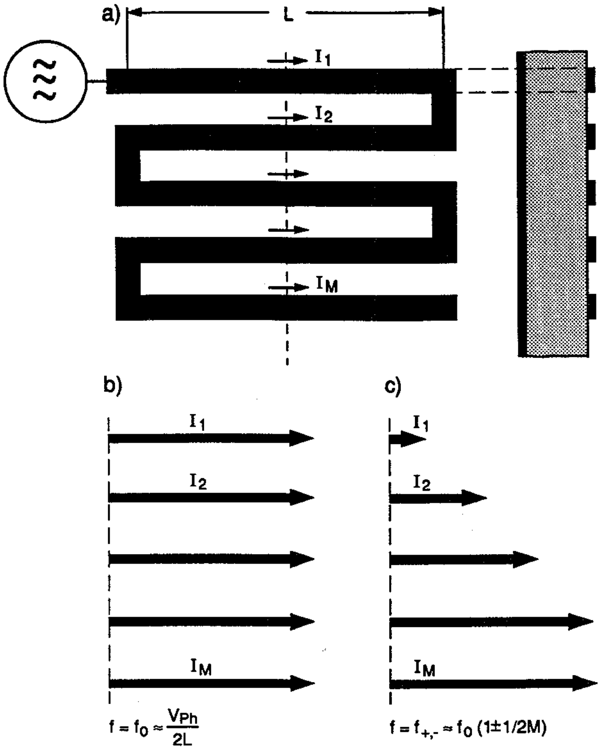

Fig. 1 :

Basic principle of meander - antenna (simplified model):

a) Geometric structure with $L << \lambda_0$.

b) Current distribution for f_0

c) Current distribution for $f_0 \pm f_0/2M$

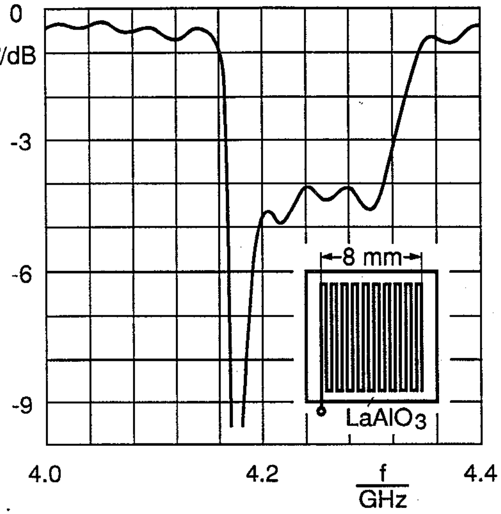

Fig. 2 :

Structure of meander antenna and experimental results: Experimentally investigated structure: YBCO strip conductor, $LaAlO_3$ substrate 10 x 10 mm^2 with a thickness of 1 mm, gold ground - plane. Length of a meander section is 8 mm and the line - width is 0.1 mm. Distance between two strips is 0.3 mm.

3. EXPERIMENTAL RESULTS

A meander antenna was realized by means of a $YBa_2Cu_3O_{7-\delta}$ thin film (thickness about 300 nm) epitaxially grown on a 1 mm thick single-crystalline $LaAlO_3$ substrate by dc-sputtering. The surface resistance [3] of the unstructured film was determined to be about 15 mΩ at 77 K and 87 GHz. The meander stripline structure according to Fig. 2 with a conductor line - width of about 100 µm was patterned by conventional photolithography and wet etching. On the backside of the substrate a gold layer was deposited. In order to investigate the microwave properties of this new antenna at 77 K it was attached on top of a cold finger and provided with a coaxial connector. The entire structure was placed in an evacuated electromagnetically transparent plexi - glass dewar. In direction perpendicular to the surface of the antenna a wide - band ridge horn - antenna was located in a distance of 1 m. Scattering from objects in the vicinity was reduced by means of appropriately located absorbers. Input reflection coefficient $S_{11} = \Gamma$ of the meander antenna as well as the transmission - factor S_{12} for the link consisting of meander - and horn - antenna was measured with an HP 8510 C vector network analyzer. Fig. 2 shows the obtained results for the input reflection coefficient Γ at 77 K. Although the antenna has only a linear size of $D = 8$ mm ($\approx \lambda_o/10$), it exhibits a 3 dB-bandwidth of about 4%. Furthermore, it possesses a typical bandpass characteristics with relatively sharp transitions to the "stopbands". In Figures 3 to 5 the frequency response is shown in a wider frequency range which allows the properties of the structure to be investigated more clearly. From the phase - response of $S_{11} = \Gamma$ in Fig. 5 one can recognize a stopband for the wave propagation on the meander structure (evanescent mode) above about 4.35 GHz. For frequencies below the " radiation window " (between 4.15 GHz and 4.35 GHz) other resonances without a sufficient radiation can be seen in Fig. 3 and 4. The " radiation stopband " above 4.35 GHz is because of the existence of nonpropagating, but evanescent modes on the meander characterized by a higher reflection loss as in the radiation stopband below 4.15 GHz (see Fig. 3). The efficiency is estimated to be higher than 60% based on experiments where the radiated power was compared to those of an antenna with known gain. This has to be compared with an efficiency of about 5 % which can be estimated for a normalconducting version of this antenna at 77 K. No power - dependence of the frequency - response was observed in the measurement range up to an input power of 20 dBm. The radiation pattern closely follows that of a magnetic dipol oriented parallel to the substrate surface and perpendicular to the meander arms.

CONCLUSIONS

The utilization of a substrate with a relatively high permittivity is a well - known mean to reduce the geometric size of a conventional microstrip patch antenna. If this " miniaturization " is accomplished without a change of the patch shape (e. g. rectangular) it results in a significant reduction of the frequency bandwidth. The presented novel microstrip meander antenna provides a mean for compensating this bandwidth - reduction within a range determined by a general size - dependent limit. It furthermore possesses a " sharp " bandpass frequency response which offers some advantage if closely spaced antenna systems for adjacent frequency bands have to be decoupled.

For this type of antenna a " sufficiently " high radiation efficiency can only be achieved if superconductive material is applied. This is due to the high radiation quality factor of electrically small antennas and furthermore due to the required narrow line - width of the conductors of the meander structure. A planar feed - system for a receiving antenna may serve as an example for potential system - applications of electrically small planar HTS antennas. The small size of each single radiation element allows a large number of different systems to be placed within a relatively small area.

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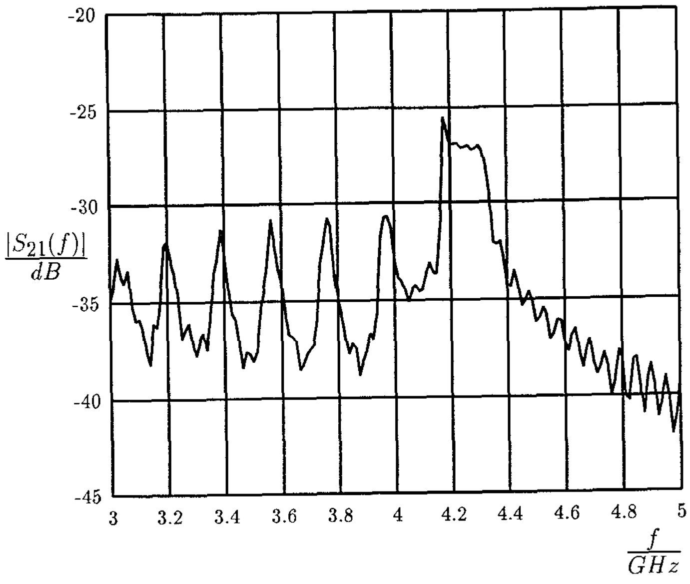

Fig. 3:
Frequency response of the transmission factor $|S_{21}(f)|$ for a 100 cm long link consisting of the HTS meander - antenna at 77 K and a wide - band ridge horn - antenna in the frequency range from 3 to 5 GHz. This figure indicates the antenna "passband" between 4.15 GHz and 4.35 GHz and a sharp drop of the transmission factor in the regime above 4.35 GHz where the meander transmission line possesses its stopband.
Below 4.15 GHz the transmission factor is reduced by more than 5 dB but exhibits maxima at those frequencies where the total length of the meander line equals a full number of half guide wavelengths.

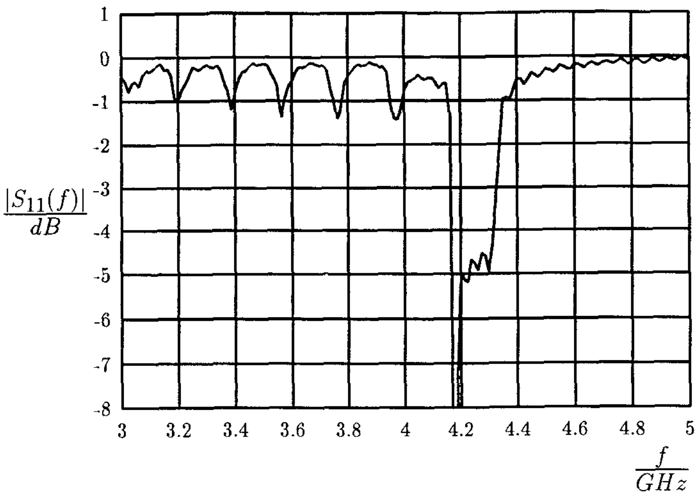

Fig 4:
Frequency response of the magnitude $|S_{11}(f)|$ of the input reflection coefficient $\Gamma = S_{11} = |S_{11}| \exp(j\Phi_{11})$ in a wide frequency range. Maxima of $|S_{11}|$ correspond to minima of $|S_{21}|$ in Fig. 3 and vice versa which indicates that dissipative effects onto the frequency response can be neglected.

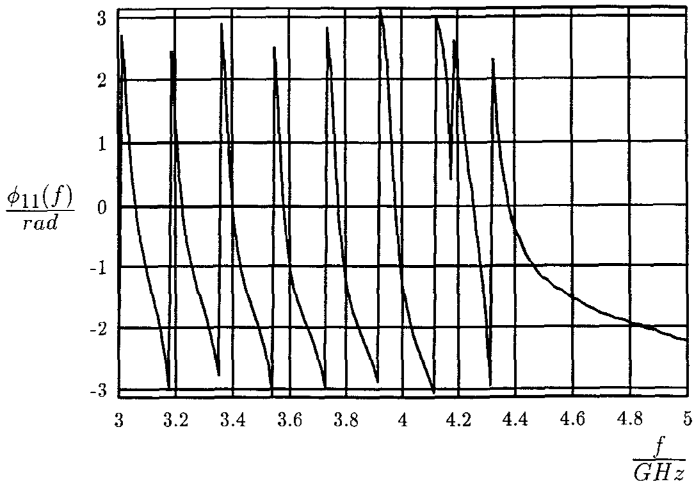

Fig. 5:
Frequency response of the phase Φ_{11} of the input reflection coefficient. The abruptly decreasing slope of the frequency dependence of Φ_{11} at frequencies above 4.35 GHz clearly indicates the transition to the stopband of the meander transmission line.