Paper

A Practical Design Consideration for Coupled-Resonator Laminated Band Elimination Filter Fabricated with LTCC of High Dielectric Constant

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A practical design procedure of coupled-resonator band elimination filter (BEF) is studied. A small-sized BEF is fabricated with Low Temperature Co-fired Ceramics (LTCC) having high dielectric constant. Deterioration of band elimination characteristic due to approach of the constituent resonators is recovered with the proposed design procedure. But, in a practical fabrication process, additional physical restrictions are placed on this structure, e.g., the length and the impedance of inter-stage transmission line make another problem for its realization. They are overcome by adjustment based on computer simulation, and a fabricated LTCC BEF shows a good performance in an experiment carried out at the 2GHz-band.

Keywords: Microwave filter, Band elimination filter, Decoupling capacitor, Coupled transmission line, LTCC

1. Introduction

Recently, in the use for portable telephones, laminated ceramic filters fabricated with Low Temperature Co-fired Ceramics (LTCC) are commonly employed due to their small-size and light-weight configuration [1), (2)], though most of them are of the bandpass type. A laminated band elimination filter (BEF), on the other hand, has been developed successfully by the present authors [(3), (4)], and the effects of coupled-resonator also have been studied [(5), (6)]. Usually, the insertion loss of BEF in the pass band is fairly smaller than that of BPF. It is achieved by attenuating undesired signals only in the specific frequency band. To fully utilize the features of BEF, the designers have to know the undesired signal frequencies a priori. However, the low insertion loss is still attractive. Thus BEF is often used as a transmitting filter for portable telephones to suppress the undesired signal in the receiving band.

Here the use of LTCC having high dielectric constant faces the following three serious problems. The demand for small size cannot provide an enough space either for distance of adjacent resonators or inter-stage transmission line length between resonators. To solve the first problem, a capacitance is added between the two resonators. Thus, we will propose a new design method, which includes cancellation of coupled-resonator effect. In the second, the inter-stage transmission line should be as short as possible due to the allowed narrow space. Hence, we will examine whether the length of the inter-stage transmission line may be made shorter than a quarter-wavelength. Thirdly, the high dielectric constant leads the characteristic impedance of the line lower than 50Ω, since a 50Ω-transmission-line requires a width of less than 10μm, which is impossible to be formed by the conventional printing method. As the filter size becomes smaller, the problems become more serious, and thus we will solve these remaining issues by adjustment based on the computer simulation.

In Section 2 of this paper, an equivalent circuit of coupled-resonator BEF and its design method are described. To help understanding, a design example is shown for a 2-stage Chebyshev BEF. In Section 3, a practical design overcoming the 2nd and 3rd issues is studied. In Section 4, an experimental laminated BEF is constructed for the 2-GHz band. Actually, the authors use the LTCC of Bi-Ca-Nb-O (BCN) system [(7)] as a trial, whose dielectric constant is 58. The experimental results show validity of the proposed concept. Finally, in Section 5, we summarize the study.

2. Coupled-Resonator BEF Design

2.1 General Description of Coupled-Resonator BEF

The exploded view of the coupled-resonator BEF, which is treated in this paper, is shown in Fig.1. The electrodes are made of silver. The thickness of the electrode is about 10μm. The coupled-resonator electrodes are fabricated on an inner-layer between ceramic sheets as a tri-plate structure. The main transmission line electrode and a decoupling capacitor electrode are fabricated on the upper adjacent ceramic layer. These two layers are sandwiched by an upper and a lower shield electrode. Here the electromagnetic coupling between resonators degrades the attenuation performance of the BEF [(4)].

The authors have reported some ways to overcome these coupling effects previously [(4), (5), (6)]. In this process, the authors have noticed that adding a capacitive coupling cancels the unwanted coupling between two resonators. In order to realize it, there are variety of structures, which include addition of a lumped element capacitor, narrowing of the gap between top part of the

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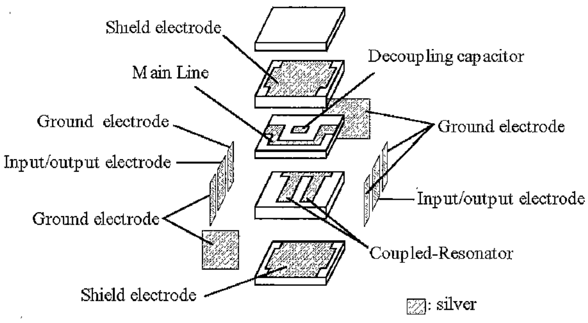
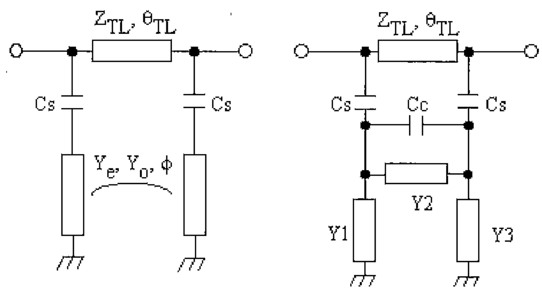


Fig. 1. Exploded view of laminated BEF.



(a) original circuit, (b) modified circuit

Fig. 2. Equivalent circuit of BEF.

two resonators, adoption of SIR (Stepped Impedance Resonator) structure and others. We will choose the simplest option, a lumped element capacitor here.

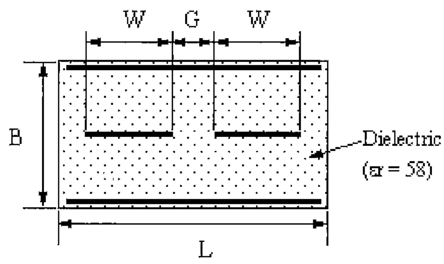
Figure 2(a) shows the circuit of the coupled-resonator BEF. The equivalent circuit of a coupled λ/4 resonator is derived easily considering the symmetry of the circuit, and thus, (a) is redescribed into (b), adding the capacitor *Cc* mentioned above. The equivalent admittance elements are given as

$$Y1 = Y3 = -jY_e \cot\phi \quad \cdots\cdots (1)$$

$$Y2 = j\frac{Y_e - Y_o}{2}\cot\phi \quad \cdots\cdots (2)$$

where Y_e and Y_o denote the characteristic admittances of the even and the odd mode, respectively, and ϕ gives the electric length of the resonator. Looking at this structure, one notices the admittance $Y2$ deteriorates the band elimination characteristics, making a short path between the two resonators. Thus, the recovery principle should be cancellation of the effect of $Y2$ at the center frequency of the BEF, that is, at ω_0. The admittance $Y2$ becomes zero at its own resonant frequency ω_p as is known from eq. (2). Therefore, we add a capacitance *Cc* parallel to $Y2$ and make the resonant frequency lower and equal to ω_0, which is the series resonant frequency of *Cs* plus $Y1$.

There is one more concern that the characteristic admittance of the resonator is not Y_b any more but Y_e because of the coupling. Here, the Y_b is the characteristic admittance without coupling between the resonators. As a result, the series resonant frequency is shifted to the lower side because Y_e is always smaller than Y_b. So as to keep the center frequency of the BEF constant, the resonator should be adjusted shorter.



(W=1.0mm, G=0.5mm, B=1.6mm)

Fig. 3. Cross sectional view of coupled line.

2.2 Design Example of BEF without Coupling At first, we will show a design example for 2-stage Chebyshev BEF without coupling between the two resonators. The specifications are assumed as follows; center frequency f_0=2.0 GHz, bandwidth 260 MHz, specific bandwidth w=0.13 and ripple=0.2 dB. We are going to use an LTCC material whose permittivity is 58 and the cross sectional dimensions are as shown in Fig.3. Since we do not have any troublesome coupling, we can use the design procedure in Ref.8. Considering the ripple value, the element values are given as g_1=1.0378, g_2=0.6745 and g_3=1.5386. Here, the element values g_k are the inductances or capacitances of the elements, which comprises the low-pass proto-type filter. We can get actual capacitance and inductance values by converting the low-pass proto-type to a band-pass configuration along with re-scaling the element values by the actual center frequency, bandwidth and source/load impedance (8).

When the input and output circuits are terminated to 50 Ω, the characteristic impedance of the inter-stage transmission line should be

$$Z_{TL} = \frac{Z_0}{\sqrt{g_0 g_3}} = 40.31\Omega \quad \cdots\cdots (3)$$

The slope parameters x_1, x_2 of each resonator become

$$\frac{x_1}{Z_0} = \frac{1}{\omega_1' g_0 g_1 w} = 7.411, \quad \frac{x_2}{Z_0} = \frac{1}{\omega_1' g_2 g_3 w} = 7.411 \quad \cdots\cdots (4)$$

Now the dimensions given in Fig.3 bring 11Ω for the calculated characteristic impedance Z_b of the resonator strip line, where the thickness of the strip line is neglected in the calculation. Thus, the following equations for the slope parameter

$$x = \frac{Z_b}{2}(\phi \sec^2\phi + \tan\phi) \quad \cdots\cdots (5)$$

gives 81.22 degree.

The series capacitance *Cs* in Fig.2 is obtained as

$$C_S = \frac{\cot\phi}{\omega_0 Z_b} = 1.117\text{pF} \quad \cdots\cdots (6)$$

Using the circuit parameters calculated above, we show the simulated transmission response of the BEF in Fig.4. The curve marked with $G=\infty$ indicates the no-coupling case designed just now, while the other curves show the case where the distance between two resonators comes smaller. As the distance decreases, they deteriorate up to the degree that they cannot be called a BEF

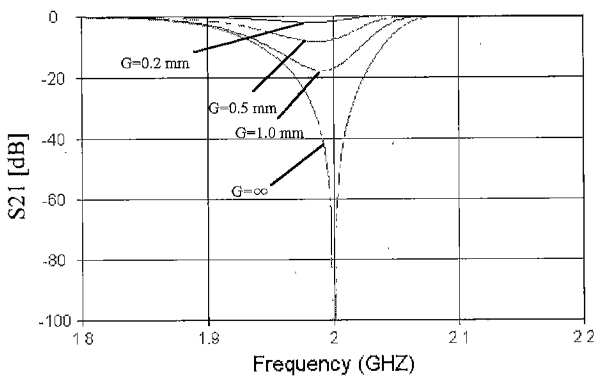


Fig. 4. Simulated transmission response of BEF without Cc.

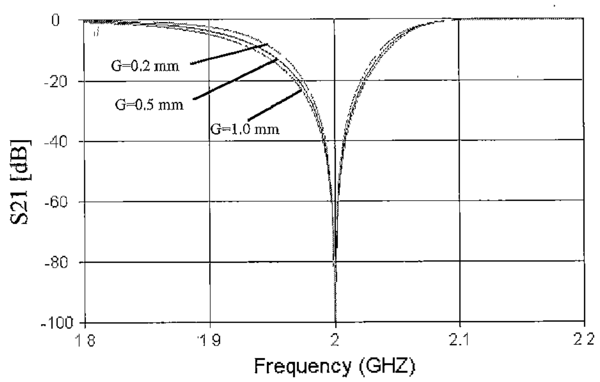


Fig. 5. Simulated transmission response of BEF with Cc.

Table 1. Circuit parameters for modified BEF.

G(mm)	0.2	0.5	1.0	mm
Ze	13.6453	12.7252	11.8706	Ohm
Zo	8.6626	10.1257	10.9327	Ohm
ϕ	80.2196	80.5571	80.8818	deg.
Cs	1.0053	1.0401	1.0760	pF
Cc	0.2891	0.1335	0.0462	pF

Table 2. Optimized circuit parameters for modified BEF.

G(mm)	0.2	0.5	1.0	mm
Ze	13.6453	12.7252	11.8706	Ohm
Zo	8.6626	10.1257	10.9327	Ohm
ϕ	80.7100	80.8200	80.9800	deg.
Cs	1.0053	1.0401	1.0760	pF
Cc	0.2808	0.1315	0.0459	pF

any more. Therefore we are encouraged to propose a new design method.

2.3 Design Example of BEF with Coupling When one makes the distance between the two resonators closer, say, to 0.5mm in the last example, induced coupling bypasses the signal, resulting in aggravation of band elimination characteristics. Now we add a capacitance *Cc* as shown in Fig.2 (b) in order to make the admittance of the parallel *Y2* and *Cc* circuits zero at the center frequency 2.0GHz. Since the parallel resonance condition is

$$\omega_0 C_c + \frac{Y_e - Y_o}{2}\cot\phi_0 = 0, \quad \cdots\cdots(7)$$

one can obtain the necessary capacitance *Cc* if ϕ_0 is given. But it is not determined at this stage. Instead, assuming that the effect of shunt admittance has been canceled by the procedure above, hence we proceed to adjustment of the resonator length. Because of the coupling, the characteristic admittance of the resonator changes to Y_e from *Yb*. Thus, the series resonance condition eq.(5) is changed as

$$x = \frac{Z_e}{2}(\phi_0 \sec^2\phi_0 + \tan\phi_0), \quad \cdots\cdots(8)$$

where one should pay attention to the change of characteristic impedance from eq.(5). The electrical length ϕ_0 is calculated numerically for the given x and Y_e. One can also refer to the table in p.740 of Ref.8. Thus ϕ_0=80.557deg is obtained for this case.

The change of resonator length affects the value of the series capacitor *Cs*. The resonance condition at ω_0 for the series resonator made of *Cs* and *Y1* (or *Y3*) is

$$Z_e \tan\phi_0 - \frac{1}{\omega_0 C_s} = 0, \quad \cdots\cdots(9)$$

since the effect of bypass admittance *Y2* is made zero as described by eq.(7). Thus *Cs* is determined to be 1.040pF.

Now *Cc* is calculated by substituting the value ϕ_0 into eq.(7). Since we have obtained all the modified BEF parameters, we will show them in Table 1 including those for *G*=1.0, 0.5, 0.2mm. But the compensation is not satisfactory if the values in Table 1 is used, because the procedures above only gives the condition for one attenuation pole out of the two. Adjusting the values in Table 1 to attain the best attenuation at the designed center frequency, one obtains the final parameters given in Table 2 and the simulated responses in Fig.5.

3. Consideration for Practical Design Problem

3.1 Effect of the inter-stage transmission line impedance

As was mentioned in Introduction, it is quite difficult to keep rather high characteristic impedance, typically 50Ω, of a transmission line made of high permittivity ceramics, due to difficulty in fabricating a thin line and the resulting excessive conductor loss. Fortunately, however, the required characteristic impedance is lower than 50Ω for a Chebyshev BEF as shown in eq.(3). In addition, degradation of the transmission and reflection characteristic is not too sensitive to the impedance value as shown in Fig.6. It describes the case where our modified design method is applied for *G*=0.2mm and then the inter-stage line is changed from the best characteristic impedance 40.3Ω to lower values. Though the reflection $|S_{11}|$ increases out of the stopband to the extent that some remedy might be needed at the passband of a serial BPF (if any), the transmission $|S_{21}|$ keeps a deep valley in spite of low characteristic impedance down to 20.3Ω.

3.2 Effect of the inter-stage transmission line length

Figure 7 shows the filter response for inter-stage line length shorter than the optimum quarter wavelength. The starting point is *G*=0.5mm, Z_{TL}=40.3Ω and θ_{TL}=90° as shown in Fig.6. The transmission characteristic is again insensitive to the parameter deviation, though the reflection characteristic is not. Thus, one can

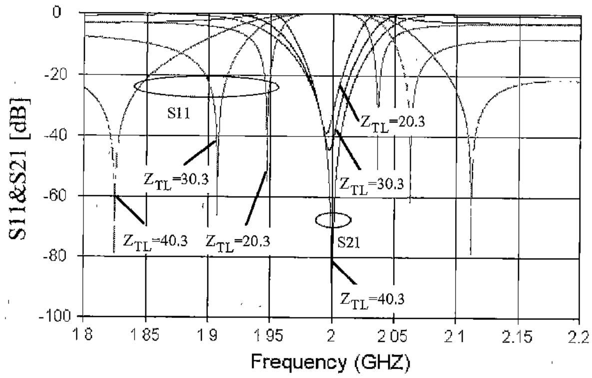


Fig. 6. Effect of characteristic impedance of inter-stage transmission line.

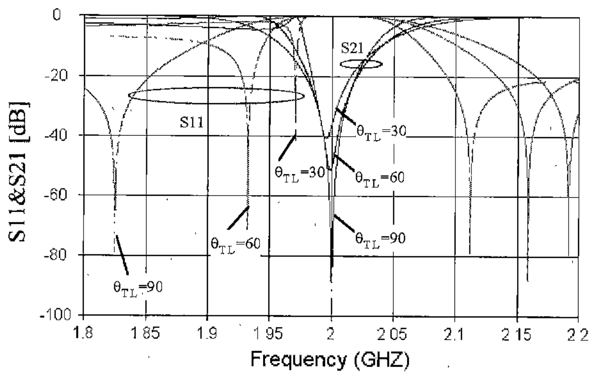


Fig. 7. Effect of length of inter-stage transmission line.

reduce the inter-stage line length as long as one finds means to recover matching at the possible passband.

These two practical requirements are quite common for realizing a small-sized and low-loss BEF. But it was elucidated above that both requirements degrade matching to the external circuits. Hence, it will be necessary to add some matching circuit if one is to introduce those measures.

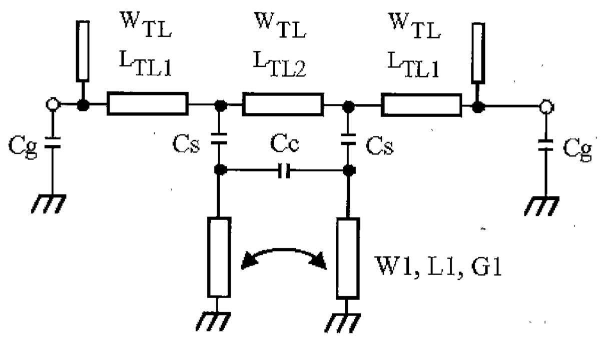
4. Experimental Result

In order to realize a laminated 2-stage BEF based on the LTCC structure, there are needed measures to match the BEF to the external circuit as mentioned in the last section. But one is required to add some more considerations, e.g., adjustment of matching to cancel the effect of the surrounding metal walls, tuning of resonators to reduce the effect of fabrication error and so on. Therefore experimental result can hardly be compared with the designed or simulated result in a strict manner. One can see the schematic diagram and circuit pattern for a BEF on a trial basis in Fig.8. We have adopted the BCN material of relative permittivity ε_r=58. The center frequency f_0=2GHz, stop band width B=260MHz are selected. The other specifications are as follows; Attenuation in the frequency band from 1970MHz to 2030MHz is more than 20dB, Insertion loss in the frequency band from 1810MHz to 1870MHz is less than 2.0dB. Each parameter for simulation is given as follows; resonator width $W1$=1.0mm, spacing $G1$=0.25mm, length $L1$=3.79mm, main line width W_{TL}=0.4mm, length L_{TL1}=2.47mm, length L_{TL2}=2.40mm, stub width 0.15mm, stub length 1.29mm, Cg=1.19pF, Cs=2.0pF, Cc=0.22pF. Here the transmission lines TL1, stub and capacitors Cg are introduced for impedance-matching purpose as mentioned in the preceding sections.

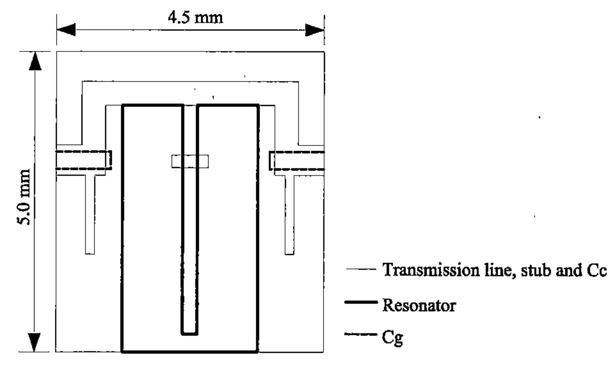
We have simulated the circuit response with and without the decoupling capacitor Cc in Fig.9, expecting improvement of the transmission characteristic around the designed frequency 2GHz. Two sintered samples with and without Cc are measured by using a vector network analyzer and the response is shown in Fig.10. The material and configuration are the same for two cases except Cc, as shown in Fig.8. Though the center frequency is shifted to the upper side by 5%, the deteriorated band elimination characteristic is evidently recovered by addition of the decoupling capacitor Cc. The attenuation more than 20dB is successfully obtained for the case with Cc. But the attenuation bandwidth is about 45MHz, which is a little bit narrower. On the other hand, the minimum attenuation is only just 12dB for the case without Cc. Regarding the insertion loss, it does not satisfy the specification of less than 2dB at this time, because of the poor manufacturing accuracy. Totally, the effect of the decoupling capacitor Cc is confirmed by this experiment. Fig.11 shows the photograph of the experimental filter. The dimensions are 4.5mm x 5.0mm x 2.0 mm. Measurement system is shown in Fig.12.

5. CONCLUSIONS

Three serious problems when constructing a practical laminated BEF with LTCC of high dielectric constant have been solved. First, degradation of band elimination characteristic due to approach of the resonators is removed by addition of a capacitor between the

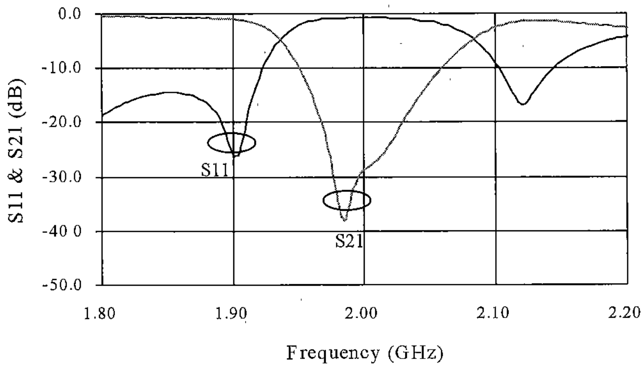


(a) Schematic diagram,

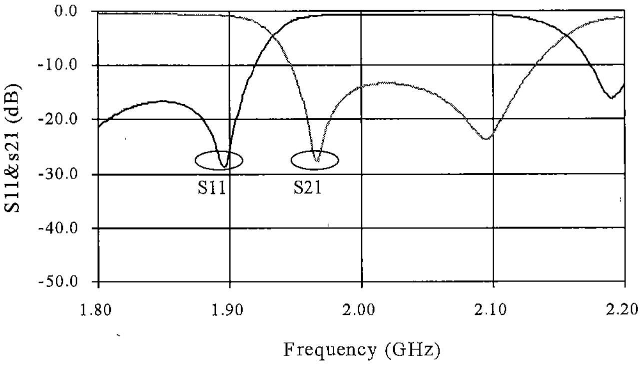


(b) perspective view of circuit pattern

Fig. 8. Schematic diagram and circuit pattern of fabricated BEF.



(a) with Cc



(b) without Cc

Fig. 9. Simulated transmission response of fabricated BEF.

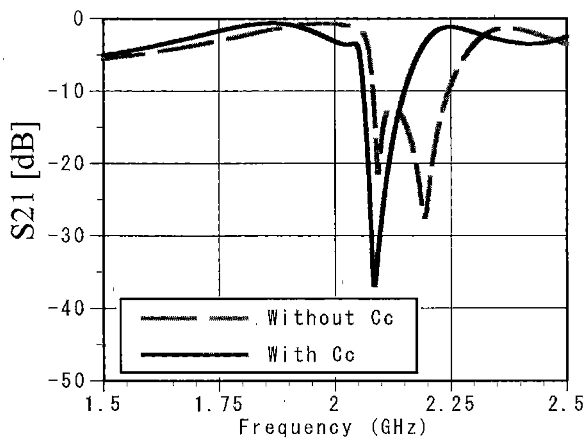


Fig. 10. Measured transmission response of fabricated BEF.

resonators. In the next, the effect of the length and the characteristic impedance of the inter-stage transmission line have been studied. The electrical length of 60 degrees is found acceptable for a practical design, and characteristic impedance as low as 20Ω is also found acceptable.

Thus, a new small sized BEF is designed and fabricated successfully.

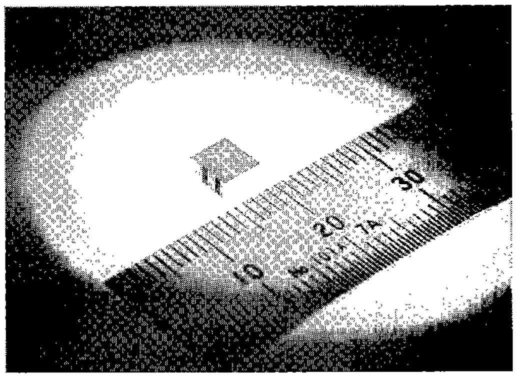


Fig. 11. Photograph of the experimental filter.

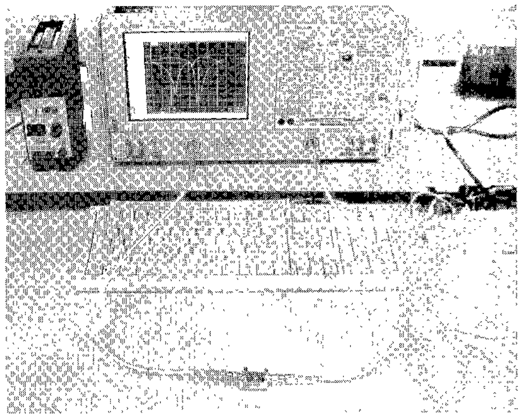


Fig. 12. Measurement system.

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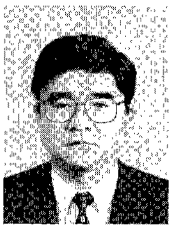

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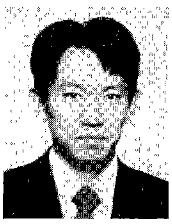

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