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Prototype Electromagnetic-Noise Filters Incorporated with Nano-Granular $Co_{41}Fe_{38}Al_{13}O_8$ Soft Ferromagnetic Thin Films on Coplanar Transmission Lines

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ABSTRACT

A non-integrated type noise filter on a Coplanar Waveguide (CPW) transmission line is demonstrated by using a highly resistive $Co_{41}Fe_{38}Al_{13}O_8$ nanogranular thin film with the dimensions of 4 mm (l) × 4 mm (w) × 0.1 μm (t). The noise suppression characteristics are evaluated without placing an insulating layer between the CPW line and the magnetic thin film. The insertion loss is very low being less than 0.3 dB and this low value is maintained up to 2 GHz. At a ferromagnetic resonance frequency of 3.3 GHz, the power loss is very large and the degree of noise attenuation is measured to be 3 dB. This level of noise attenuation is still small for real applications; however, considering the small magnetic volume used in this work, further improvement is expected by simply increasing the magnetic volume and by integrating the magnetic thin film into the CPW transmission line.

Key words **: *Nano-granular thin film, Ferromagnetic resonance, Electromagnetic noise, Noise suppressor, Coplanar transmission line***

1. Introduction

A general means of improving the performance of magneto-electronic devices is to increase their operational frequency. However, an electromagnetic noise is a serious concern at high frequencies. And this is particularly true for the GHz frequency range, within which most current wireless communications devices operate. Therefore, developing countermeasures for suppressing electromagnetic noise in the frequency range of several hundred MHz to several GHz has become an important technical issue. Magnetic materials have played an important role in effectively suppressing electromagnetic noise, where the basic mechanism involved has been the loss generation of Ferromagnetic Resonance (FMR). Co-Zr-Nb and Co-Pd-Al-O sputtered magnetic films were previously used for an integrated countermeasure of electromagnetic noise emission on a Radio Frequency (RF) integrated transmission line.[1-3] Recently, spin sprayed Ni-Zn-(Co) soft ferrite films with high electrical resistivity were reported to show good attenuation characteristics against the RF electromagnetic noise on a CPW transmission line.[4]

Nanogranular Co-Fe-Al-O thin films were first developed by Ohnuma *et al.*[5] and, later, by Sohn *et al.*[6,7] These films exhibit a high saturation magnetization ($4\pi M_S$) and a high anisotropy field (H_K), combined with large electrical resistivity, resulting in excellent high-frequency magnetic properties such as a high FMR frequency and a large real part of permeability (μ_r').[5-7] Therefore, it is expected that the Co-Fe-Al-O thin films will be suited for an RF electromagnetic noise attenuation device on a CPW transmission line.

Normally, an insulating layer (polyimide film, for example) is disposed between a magnetic layer and a CPW line. This is necessary, because the magnetic layer used is usually based on metals with low electrical resistivity. Obviously, the use of an insulating layer is not desirable causing additional complication during the device fabrication. In the case of a polyimide film, which is used frequently as an insulator,[1-3] at least three additional processes (two spin-coating processes and one chemical-mechanical process) are required. Furthermore, the separation between the magnetic layer and CPW line increases with the inclusion of an insulating layer, and this usually deteriorates the attenuation characteristics. These drawbacks make it highly desirable eliminate any insulating layer between a magnetic layer and a CPW line. This development can be made possible if the magnetic thin film is an insulator or exhibits very high electrical resistivity.

Recently, good attenuation characteristics were observed for a spin sprayed Ni-Zn-(Co) soft ferrite film without adding an insulator layer.[4] The Co-Fe-Al-O thin films, the matrix of which is an insulating Al-O phase, exhibit relatively high electrical resistivity, being in the range of 300 to 400 μΩcm, although their resistivity is still far lower than that of ferrites. With this level of electrical resistivity, it is

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expected that good attenuation characteristics can be obtained without inserting an insulating layer. The main purpose of the present study is to test this expectation. A Co-Fe-Al-O thin film is directly placed on a CPW line to form a non-integrated noise suppressor, and its attenuation characteristics are investigated over a wide frequency range.

2. Experimental Procedure

A $Co_{41}Fe_{38}Al_{13}O_8$ nanogranular thin film with a thickness of 0.1 μm was prepared by RF magnetron sputtering. The film was deposited on a Si substrate in a static field of 1 kOe to induce uniaxial magnetic anisotropy. The FMR frequency was determined from the frequency profile of complex permeability, $\mu_r = \mu_r' + j\mu_r''$, measured up to 9 GHz with a pick-up coil type permeameter. The film deposited on a Si substrate was mounted on top of a CPW transmission line. It is noted that the film surface, not the Si substrate, was in contact with the CPW line. The proximity between the magnetic thin film and the CPW line can be varied with an applied pressure; however, in the present study, no pressure was intentionally applied. The dimensions of the film were 4 mm (l) × 4 mm (w) × 0.1 μm (t). Following the Muller and Hillberg equations,[8] a CPW transmission line with a characteristic impedance of 50 Ω was designed for a signal line width of 50 μm and a thickness of 3 μm on a 7059 corning glass substrate. Fig. 1 illustrates the structure of the CPW transmission line in detail. The S-parameters (S_{11} and S_{21}) were measured with a HP 8720D network analyzer in the frequency range of 0.1 to 20 GHz. Two Ground-Signal-Ground (GSG) pin type wafer probes were in mechanical contact with both ends of the CPW transmission line. Here, it is necessary to explain the S-parameters, albeit very briefly, by referring to Fig. 1(b). An input signal (or noise) is introduced from the left-hand side and is partly reflected at the left-hand end of the magnetic film. This reflected signal is called S_{11}, the reflection scattering parameter. The counterpart to this signal goes into the magnetic film portion where a certain degree of attenuation occurs due to FMR losses. Then the transmission signal or noise, called the transmission scattering parameter (S_{21}), reaches the right-hand end of the CPW line.

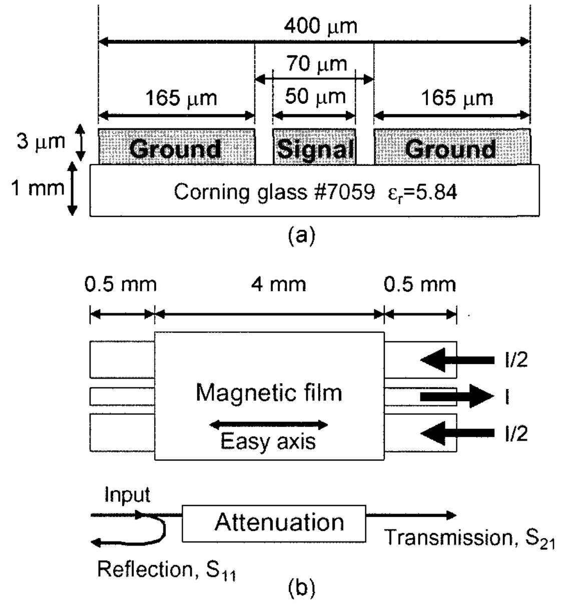

Fig. 1. (a) the cross-sectional view of the CPW transmission line (with detailed dimensions) used in this work and (b) a top view of a noise filter showing a magnetic film on top of the CPW transmission line. Note that the dimensions are not to scale.

3. Results and Discussion

The considered $Co_{41}Fe_{38}Al_{13}O_8$ nanogranular thin film exhibits a very large electrical resistivity (ρ) of 374 μΩcm, together with a large H_K of 50 Oe, a hard axis coercivity of 1.25 Oe, and $4\pi M_S$ of 12.9 kG.

Fig. 2 shows the results for experimental (indicated by symbols) and theoretical (denoted by lines) spectra of the relative permeability for the $Co_{41}Fe_{38}Al_{13}O_8$ film. The scanned frequency range is very high, being up to 9 GHz. Both the real and imaginary parts of the effective permeability are shown in the figure. The theoretical permeability spectra are computed by using the Landau-Lifshitz-Gilbert equation. There are 5 input parameters in the equation: $4\pi M_S$, H_K, ρ, the film thickness (t) and the damping constant (α). Among these, α is only the fitting parameter, the rest being taken experimentally. The agreement between the experimental and theoretical results is reasonable in most cases. The damping constant extracted from the fit is 0.0135. This magnitude of damping is considered to be reasonable in this kind of materials. During the permeability measurements, the excitation field was applied in the direc-

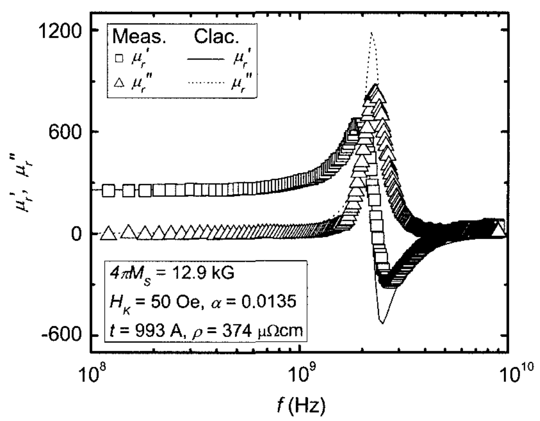

Fig. 2. Experimental (indicated by symbols) and theoretical (denoted by lines) spectra of the relative permeability for sample B over a wide frequency range up to 9 GHz. Both the real and imaginary parts of the effective permeability are shown. The theoretical permeability spectra are computed from the Landau-Lifshitz-Gilbert equation.

tion perpendicular to the easy axis. The real part of the permeability (μ') is nearly flat up to 1 GHz. In addition, in this frequency range, the imaginary part of the permeability is very low. The imaginary part (μ'') shows a peak at f_R (= 2.24 GHz). The measured value of the (pseudo) dc permeability is 260, and this value is in excellent agreement with the calculated value of 258 based on the rotation magnetization mechanism. This agreement indicates that the magnetization mainly occurs by spin rotation.

The present CPW transmission line device (see Fig. 1) consists of three parallel Cu lines. The line in the center is the signal line and the two lines at the sides are the ground lines. A magnetic film is mounted on top of the CPW line to absorb unwanted noise. Fig. 3(a) shows the frequency dependence of the transmitted (S_{21}) and reflected (S_{11}) scattering parameters for a non-integrated CPW transmission line incorporated with the present $Co_{41}Fe_{38}Al_{13}O_8$ thin film. The noise attenuation caused by a dielectric loss is smaller than that by FMR and eddy current losses.[2,3] The FMR and eddy current losses are therefore considered as the main sources of noise attenuation. In order to use the FMR loss as the noise attenuation, the easy axis of the magnetic film should be parallel to the direction of the wave propagation ($\boldsymbol{h}_{rf}$) in the CPW transmission line (see Fig. 1(b)). The insertion loss of the present $Co_{41}Fe_{38}Al_{13}O_8$ incorporated CPW transmission line, which can be obtained from the frequency dependence of S_{21}, is very low (less than 0.3 dB), and this value is maintained up to 2 GHz. The degree of noise suppression (intensity of S_{21} parameter) is about 3 dB up to 20 GHz. A minimum in the frequency dependence of S_{21} is observed at 3.3 GHz. At the same frequency, a maximum in S_{11} occurs. The value of S_{11} is maintained very low, at lower than −30 dB for up to 2 GHz, above which it rapidly increases, reaching a maximum at a frequency of 3.3 GHz. These maximum and minimum peaks in the frequency dependence of S_{11} and S_{21} are probably due to the FMR loss of the $Co_{41}Fe_{38}Al_{13}O_8$ film mounted on top of the CPW line. This value of f_R is substantially higher than that of 2.24 GHz obtained with a pick-up coil type permeameter (see Fig. 2). Since exactly the same sample (including the dimensions) was considered in both cases, this disagreement appears somewhat strange. With the lateral dimensions of 4 × 4 mm, there should not be any substantial shape anisotropy in the present sample. However, it is found that there exists an effective shape anisotropy due to the geometry of the CPW transmission line. Although essentially no shape anisotropy is expected from the present sample dimensions, the field generated from the CPW signal line is very much localized, resulting in localized magnetization and hence shape anisotropy. This is clearly supported from a Finite Element Method (FEM) computer simulation with a commercial simulation package (HFSS Version 8.5). Some of the results are shown in Fig. 4, where the magnetic field direction of the $Co_{41}Fe_{38}Al_{13}O_8$ loaded CPW transmission line is displayed at an FMR frequency of 3.3 GHz. A practically useful magnetic field to magnetize the mounted film is distributed along the center transmission line (the signal line). Considering the present geometry of the CPW transmission line, the effective shape anisotropy essentially depends on the effective width of the magnetic thin film, which is similar to or is slightly greater than the width of the signal line. From Fig. 4, it is seen that the area of localized magnetization is very small and it has a very high aspect ratio (50~65 µm in width × 2 mm in length), resulting in a high effective shape anisotropy. Fig. 5

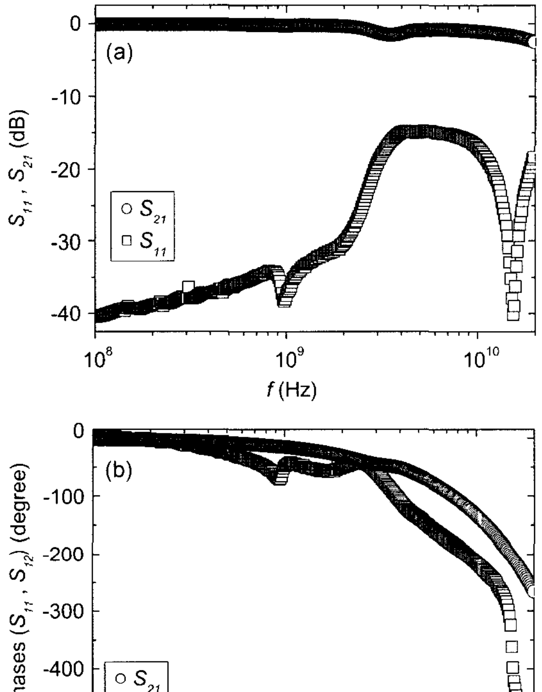

Fig. 3. The frequency dependences of (a) the transmitted (S_{21}) and reflected (S_{11}) scattering parameters and (b) the phase shift of S_{21} and S_{11} for a non-integrated CPW transmission line incorporated with a Co-Fe-Al-O thin film.

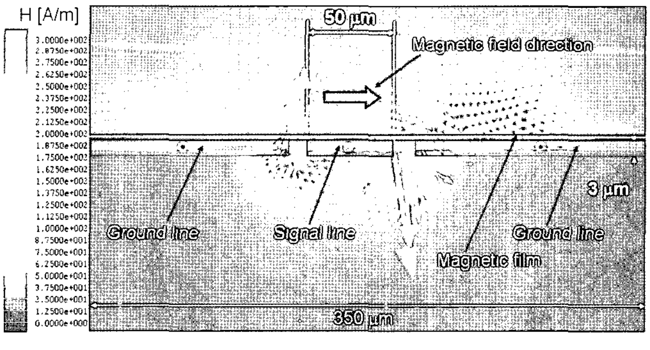

Fig. 4. The direction of magnetic field generated from the CPW transmission line incorporated with a 0.1 µm thick Co-Fe-Al-O film with a resonance frequency of 3.3 GHz.

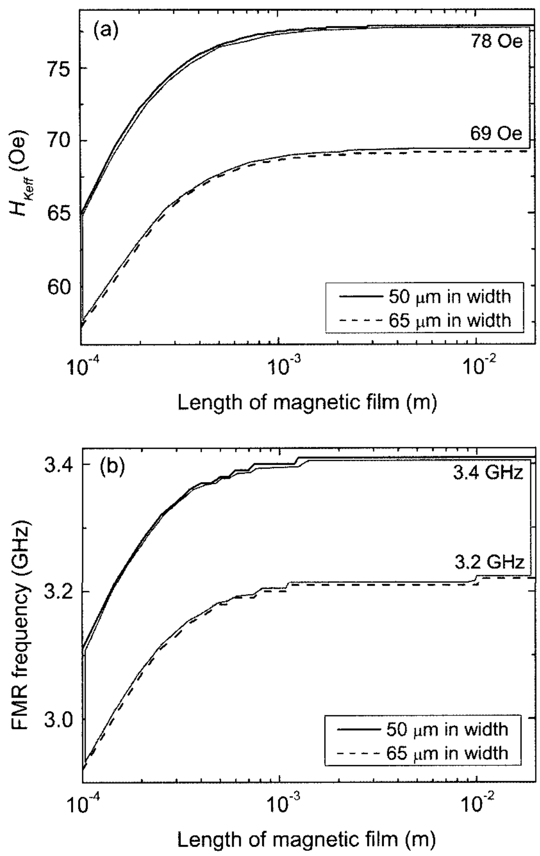

Fig. 5. Calculated sample length dependence of (a) effective anisotropy fields and (b) FMR frequency of the covering $Co_{41}Fe_{38}Al_{13}O_8$ film with the width of 50~65 μm. The thickness is fixed at 0.1 μm.

shows the calculated results for (a) the effective shape anisotropy and (b) the FMR frequency as a function of the sample length when the sample width is assumed to be 50 or 65 μm. Note that the sample thickness is 0.1 μm. The total anisotropy field, which is the sum of the intrinsic (induced) anisotropy (40 Oe in the present case) and the shape anisotropy, is used to calculate the FMR frequency. The values of the FMR frequency are, respectively, 3.4 GHz and 3.2 GHz when the widths are assumed to be 50 μm and 65 μm. The observed FMR frequency is 3.3 GHz, so the effective width is expected to be in the range of 50 μm and 65 μm.

In addition to the maximum peak in the frequency dependence of S_{11}, there are two minimum peaks observed at about 1 and 15 GHz. The peak at 15 GHz is considered to be due to dimensional losses, often observed previously.[9-12] The cause of the peak at 1 GHz is not clear yet, however. According to the electrical length principle (also referred to as the quarter wavelength rule),[9-12] the dimensional losses are closely related to the length of a magnetic film mounted onto a transmission line. In order to avoid dimensional losses, the length of a magnetic film should be less than a quarter wavelength of the highest operating frequency. The length of the Co-Fe-Al-O magnetic film used in this study is 4 mm, which is greater than the quarter wavelength (3.75 mm) at 20 GHz.

In Fig. 3(b), the frequency dependences of the phase-shift are shown for S_{11} and S_{21}. A minimum peak in the frequency dependence of the phase-shift in S_{21} is observed at 3.3 GHz, the same frequency for the FMR peak observed in the frequency dependence of S_{21} (Fig. 3(a)). Although the peak intensity is not as significant as that observed in the frequency dependence of S_{21}, this peak is due to the FMR loss. One maximum and two minimum peaks are observed in the frequency dependence of the phase-shift in S_{11}, similarly to the frequency dependence of S_{11}.

Two points can be noted from the results shown in Fig. 3(a) and (b). One is that the intensity of the reflected signal rapidly increases while its phase-shift decreases as the FMR occurs. The behavior of the transmitted signal is just opposite; namely, the intensity of the transmitted signal decreases and its phase-shift increases. The other point is that the present $Co_{41}Fe_{38}Al_{13}O_8$ film is potentially very suitable for a low-frequency pass-band filter with a pass-band of up to 2 GHz.

Fig. 6(a) again shows the frequency dependence of S_{21} for

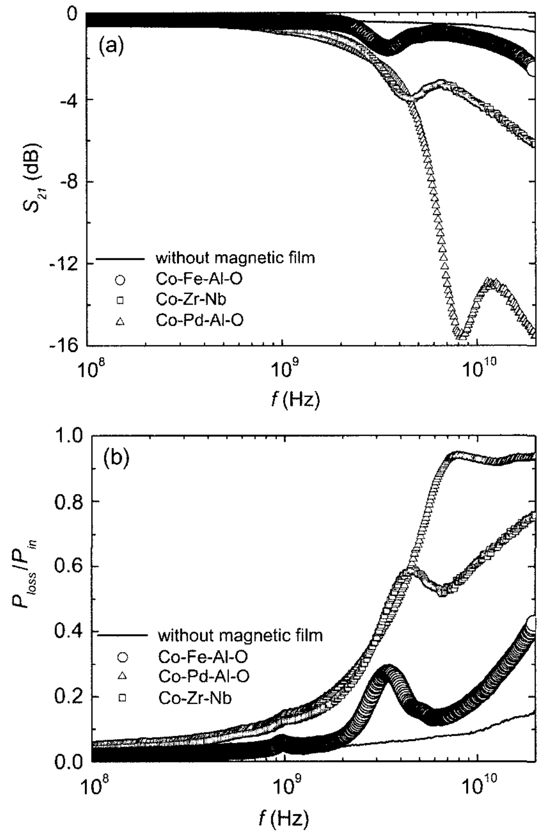

Fig. 6. The frequency dependence of (a) the transmitted scattering parameter (S_{21}) and (b) the power loss for a non-integrated CPW transmission line incorporated with a Co-Fe-Al-O thin film. The results for the bare CPW transmission line (no magnetic thin film loaded) and other non-integrated noise filters using Co-Zr-Nb and Co-Pd-Al-O magnetic films[2] are also shown for comparison.

the present non-integrated CPW transmission line incorporated with the Co-Fe-Al-O thin film, mainly to compare the present results with those for the bare CPW transmission line (no magnetic thin film loaded) and other non-integrated noise suppressors using Co-Zr-Nb and Co-Pd-Al-O magnetic films.[2)] The noise attenuation of 3 dB up to 20 GHz for the $Co_{41}Fe_{38}Al_{13}O_8$ film incorporated CPW line is small compared with the attenuation observed in the Co-Zr-Nb and Co-Pd-Al-O incorporated noise filters.[2,3)] However, considering that the volume of the $Co_{41}Fe_{38}Al_{13}O_8$ film on the CPW transmission line is about 38 times smaller than that of Co-Zr-Nb and Co-Pd-Al-O films, the S_{21} value of 3 dB achieved in this work is considered significant. The degree of noise suppression is reported to be proportional to the volume of a magnetic film incorporated on a CPW transmission line.[2,3)] Note that the dimensions of Co-Zr-Nb and Co-Pd-Al-O magnetic films on CPW transmission lines are 15 mm × 2 mm × 2 μm and those of the signal line are 15.2 mm × 50 μm × 3 μm. Note also that, in both cases, a polyimide-insulation layer with thickness of 7.5 μm was placed between the magnetic film and the CPW transmission line and, for enhanced proximity, a mechanical pressure was applied on the loaded magnetic films during the measurement. On the other hand, no pressure was intentionally applied for the $Co_{41}Fe_{38}Al_{13}O_8$ loaded CPW transmission line. The attenuation characteristics are expected to improve with an applied pressure. The results shown in Fig. 6(a) were obtained for non-integrated devices. The most common and efficient way of enhancing the proximity is to integrate the Co-Fe-Al-O film on the CPW line.

Fig. 6(b) shows the frequency profile of the power loss of the $Co_{41}Fe_{38}Al_{13}O_8$ incorporated CPW transmission line. Similar results for Co-Zr-Nb and Co-Pd-Al-O mounted structures and the bare transmission line are also shown for comparison. A large loss peak appears at 3.3 GHz, which is identical to the minimum of the attenuation (Fig. 3(a)). This loss peak is therefore due to the FMR loss generation. The other noise filters with larger magnetic volume show a high degree of loss generation. A large loss generation is expected when the volumes of the present nanogranular $Co_{41}Fe_{38}Al_{13}O_8$ magnetic film is large. It is particularly noted that, below 2 GHz (a possible pass-band), the insertion loss of the present device is as small as the bare transmission line. This implies that a $Co_{41}Fe_{38}Al_{13}O_8$ film with a high ρ is a good candidate for an RF noise filter even without an insulator layer between the magnetic thin film and the CPW transmission line. Work is currently under way to improve the noise suppression characteristics. Some parameters under consideration are the sample dimensions and the width of the signal line (which may affect the magnitude and frequency range of power loss generation).

4. Conclusions

A non-integrated type CPW transmission line incorporated with a highly resistive $Co_{41}Fe_{38}Al_{13}O_8$ magnetic thin film has been considered for application to a noise filter. The dimensions of the film were 4 mm (l) × 4 mm (w) × 0.1 μm (t). No insulating layer was disposed between the CPW line and the magnetic film. The insertion loss was very low, being less than 0.3 dB, and this value was maintained over 2 GHz, a possible pass-band. Our observations suggest that the considered $Co_{41}Fe_{38}Al_{13}O_8$ thin film is suitable for a RF noise filter. The degree of noise suppression was 3 dB up to 20 GHz. The absolute magnitude of the attenuation was considered to be insufficient for real applications, but this can be increased by increasing the magnetic volume and by integrating the magnetic thin film into the CPW transmission line. Research along these lines is now being conducted.

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