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Non-Linear Behaviour in Commonly Used Non-Polar Dielectrics at Microwave Frequencies in Space RF Components

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Abstract

In space RF communications payloads, it is increasingly required that high-power multi-channel transmitters and broadband receivers have shared, or closely adjacent RF feeds. Because of the large power level difference between the transmit and receive signals and the limitation of frequency allocation, harmonics generation due to passive non-linearities in the high-power transmission path can be a serious problem. This paper describes how to determine the signal levels and dominant mechanisms associated with non-linear dielectric behaviour in this context. A novel measurement system for testing dielectric samples is described and measurement results are provided for commonly used microwave dielectrics.

1. Introduction

Although harmonics generation is a ubiquitous phenomenon, very little is known of the underlying causative mechanisms, relating to either conductors or dielectrics. There is a large number of candidate mechanisms and it is likely that several may contribute at any given site of occurrence. There currently exists no data on the levels of the harmonics to be expected from commonly used dielectric materials nor have any studies identitified the dominant mechanisms. As greater demand is placed

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upon system performance, it is becoming increasingly difficult to provide adequate harmonic generation immunity in the absence of data. The purpose of this work is to provide an improved understanding of causes and effects of the non-linearity of dielectrics, leading to improvements in RF system design. The specific objectives are as follows:

- to design and develop a measurement system whereby the non-linear behaviour of dielectric materials under test can be measured;
- to characterize the non-linear behaviour of dielectrics in common use in microwave RF engineering, such as PTFE and polystyrene

2. The Measurement System

The measurement system is a new design of harmonic detector, implemented in coaxial components. The system is designed for 1.56 GHz, to detect the 3rd harmonic at 4.68 GHz, due to any significant non-linear behaviour of dielectric test samples. Dielectric samples are tested in a coaxial cavity, where they are exposed to a high uniform electric field. Because the level of system residual 3rd harmonic must be kept to a minimum, all components are in-house designs in which metal-to-metal junctions are absent from all critical sections in the current path. Important features are the use of contactless cable entry for critical components and fully demountable contactless coaxial connectors on the test cavity.

2.1 System Configuration

A block diagram of the 3rd harmonic measurement setup is given in Fig. 1. A source signal of 1.56 GHz, originated from a phase locked oscillator, is amplified by a separate power amplifier to give an output power up to 49 dBm (80 Watts).

The source signal passes through a diplexer using two hybrids and two low pass filters and thence to the input port of the test cavity. The low pass filters pass only the signal at the source frequency and attenuate any harmonics which may be generated in the oscillator or in the power amplifier. The diplexer provides a test signal to the cavity and couples the 3rd harmonic which may be generated in the test chamber due to any non-linear behaviour of the sample under test.

This consists of a high pass filter which attenuates the source frequency and passes the 3rd harmonic to the input port of the spectrum analyser. Source signal power is absorbed in a quiet load. This consists of two semirigid coaxial cables, UT-250 with length 45 m, followed by UT-141 with length 20 m, terminated by a lumped load. The total one way attenuation for the quiet load is 30 dB.

The test chamber is a tunable quarter-wave coaxial cavity resonator which satisfies the following requirements:

- flexibility to accommodate and exchange test samples.
- the test sample can be tested under controlled conditions
- good matching between input and output ports. This is important since the system residual can be degraded by current standing waves.
- good linearity is essential. If the test chamber construction includes non-linear materials or vulnerable junctions, the consequent increase in the system residual intermodulation will mask the intermodulation signals produced by the test samples, effectively reducing the dynamic range of the measurement system.
- a high uniform field at the position of the test sample.

The test cavity is machined in brass and is shown in Figure 2. It incorporates contactless connection at cable entry, one piece body/resonator construction and a contactless plunger to control the gap capacitance. Past experience in the design of low passive intermodulation coaxial components has shown that these features are important in achieving a low residual. The test field is determined from measurement of the cavity Q and the source signal power, given the cavity geometry. The cavity loaded Q is in the region of 130.

2.2 The System Performance

The electrical performance of the system has been tested using a "Wiltron-360" network analyser. Figure 3 shows the transmission of the source signal and absolute attenuation for the harmonics at the output of the test chamber. Figure 4 shows the absolute attenuation for the source signal and transmission of the 3rd harmonic at the output of the high pass filter.

The system noise flour is -125 dBm and the 3rd order residual is -115 dBm at a source signal power of 32 W and increases at 3dB/dB. It should be noted that these figures should be related to the field in the test cavity, rather than the source power, as in a conventional two tone system.

3. Dielectrics Non-linear Causative Mechanisms

The candidate non-linear mechanisms which may reasonably be suspected as significant causes of dielectric harmonics generation are considered to be non-linear permittivity, electrostriction and temperature coefficient of permittivity. Many potential causes of harmonics generation arise from the interaction of two or more linear mechanisms which may give rise to multi-order non-linear behaviour. This results in a bewildering number of possible combinations. An outline theoretical analysis is provided for the candidate mechanisms and their relative importance is estimated, based on theoretical considerations.

3.1 Non-linear Permittivity

The linear relationship between polarisation, P, and electric field strength, E, in dielectrics is expressed by.

$$P = \varepsilon_0 \chi E \qquad (1)$$

where χ is the susceptibility and ε_0 is the permittivity of free space is a consequence of the small mean displacement of bound charges and ceases to apply at high fields [6, 7, 8]. The value for the field at which deviation from linearity becomes apparent is given as around 1000 V/mm [3]. This implies high, but not unreasonable, current densities in the dielectric at microwave frequencies. The non-linear polarisation may be modelled as a power series of susceptibility terms. Only odd powers will be present for dielectrics which do not exhibit spontaneous polarisation, since a polarity reversal in the electric field reverses the direction of polarisation but does not alter its intensity. The first non-linear term to become significant is cubic in the electric field:

$$P = \varepsilon_0(\chi E + \xi E^3) \quad (2)$$

Where ξ is the third order susceptibility coefficient. This gives rise to a current term that is also proportional to the cube of the electric field and so third order intermodulation products will be generated. Alternatively, if this behaviour is expressed as a non-linear relative permittivity, ε_r, so that $P = \varepsilon_0(\varepsilon_r - 1)E$, then the first non-linear term may be described as quadratic (since $\varepsilon_r = \chi + \xi E^2$) and only even terms exist. For dielectric materials which exhibit spontaneous polarisation, deviations from linear behaviour may become apparent at much lower field strengths and both odd and even powers are possible. Stauss G. H. [3] dismiss non-linear permittivity as a source of harmonics generation in dielectrics on the grounds that it is less significant than the indirect modulation of permittivity by means of electrostriction It should be noted, however, that the examples given are good non-polar dielectrics such as teflon which are selected for their desirable properties as insulators at radio frequencies and are of high purity. Thus only electronic polarisation contributes to the relative permittivity and these materials are not representative of dielectrics in general. Ionisation loss occurs in solids which contain trapped gas. It only occurs when the electric field strength exceeds a critical value, above which the loss tangent rises rapidly with any increase in the field. Thus the imaginary component of the complex permittivity becomes non-linear and intermodulation components could appear in the conduction current. The increased power dissipation can also result in significantly greater heating of the dielectric.

3.2 Temperature Coefficient of Permittivity

The permittivity of dielectrics which only exhibit electronic polarisation typically have small negative temperature coefficients of around 0.01% C^{-1}. This is primarily due to the reduction of density as the material expands. The same effect also tends to reduce atomic polarisation; but for many materials this is more than compensated by the reduced interatomic forces in a less dense medium. This results in a positive temperature coefficient of, typically, 0.01% C^{-1}. There are exceptions to this: Titanium dioxide, for example, has a negative temperature coefficient of permittivity at room temperature. As these forms of polarisation result in very small dielectric losses at microwave frequencies, they do not contribute significantly to loss tangent [9, 10].

Orientational polarisation and ionic relaxation polarisation also generally make a positive contribution to the temperature coefficient of permittivity. In some materials, orientational polarisation can exhibit much larger positive and negative temperature coefficients over a certain ranges is often associated with the melting point, but may begin at a lower temperature while the material is still a solid. Ionic relaxation polarisation exhibits an approximately exponential increase in the loss tangent with temperature. For orientational polarisation, the loss tangent typically rises to a maximum (at a temperature which depends on the frequency) and then falls, before rising again as the increase in conductivity with temperature becomes significant.

Interfacial polarisation is likely to be strongly influenced by temperature since it relies on the presence of free charges, but the nature of this effect will depend on the particular materials involved. In dielectrics which do not exhibit interfacial polarisation, (typically exponential) increase in carrier density and conductivity with temperature is responsible for positive contribution to the overall temperature coefficient of the loss tangent. This is more significant for those materials which are poor insulators, and at high temperatures. It has less effect on the loss tangent at higher frequencies, where a greater proportion of the current is conveyed by polarisation mechanisms

3.3 Electrostriction

Electrostriction is the volume change due to the variation of energy density in a dielectric under RF excitation. The change in volume causes a quadratic dependence of permittivity upon the electric field. Resulting permittivity variations at the fundamental and harmonics of the input frequency modulate the primary fields leading to the generation of harmonics.

If high field polarisation is non-linear in the field strength, the dependence of the dielectric displacement D on the field strength will also be non-linear [4]:

$$D = \varepsilon_0 E + P = \varepsilon_0 E + \varepsilon_0(\chi E + \xi E^3) \qquad (3)$$

When measurements of the non-linear effects are made by superposing a low intensity alternating field on a static field of high intensity, the measurement results is the field-dependent incremental dielectric permittivity ε_E which is given by:

$$\varepsilon_E = \frac{\partial D}{\partial E} = \varepsilon + 3\varepsilon_0 \xi E^2 \qquad (4)$$

Where $\varepsilon = \varepsilon_r \varepsilon_0$ and $\varepsilon_r = (1+\chi)$ hence;

$$\frac{\Delta\varepsilon}{E^2} = \frac{\varepsilon_E - \varepsilon}{E^2} = 3\varepsilon_0 \xi \qquad (5)$$

The non-linear effect is then characterised by the quantity $\frac{\Delta\varepsilon}{E^2}$

The experimental situation is as follows: the dielectric sample is situated between the resonator rod and the top wall of the cavity. Samples consist of 1 mm thick discs, lightly held in place, i.e. under constant pressure (p). The variation in the dielectric permittivity is given by

$$\varepsilon_E = \left(\frac{\partial D}{\partial E}\right)_{T,d} + \left(\frac{\partial D}{\partial d}\right)_{T,E}\left(\frac{\partial d}{\partial E}\right)_{T,P} \qquad (6)$$

where T, d denotes to the temperature and density of the sample under test. The first term of Eq. 6 is the contribution to ε_E due to the electrostriction; denoting this term by $\Delta\varepsilon_e$ [3].

$$\Delta\varepsilon_e = \left(\frac{\partial D}{\partial E}\right)_{T,d} = E^2 \frac{1}{k} d^2 \left(\frac{\partial \varepsilon}{\partial p}\right)_T \qquad (7)$$

Thus, the magnitude of the contribution to the dielectric permittivity due to the electrostriction can be calculated from the bulk modulus (k) and the dependence of the permittivity on either the density or the pressure.

Intermodulation powers developed by this mechanism vary in inverse proportion to the square of the bulk modulus of the dielectric. The modulus, k, is related to the elasticity modulus and Poisson's ratio by the following equation [1]:

$$k = \frac{E_s}{3(1-2\nu)} \tag{8}$$

where E_s = elasticity modulus, and ν = Poission's ratio There is an associated thermal effect so that the volume change can also result in a temperature variation. Electrostriction is expected to be the principal source of non-linearity in good non-polar dielectrics such as PTFE and cross-linked polystyrene because the bulk modulus of these materials is very small.

4. Analysis of Results

Any variation in dielectric properties with the applied field will serve to modulate incoming signal currents. The 3rd harmonic intermodulation level generated due to the non-linear mechanisms of the dielectric sample under test, excited by a uniform field, can be derived based on power series as follows [5]:

$$D = \varepsilon_0 \varepsilon_r (E + \alpha E^3 + \beta E^5 + \ldots) \tag{9}$$

where α and β are coefficients of non-linear dielectric behaviour.

$$E = E_0 \sin\omega t$$

$$i = \varepsilon_0 \varepsilon_r \frac{\partial}{\partial t}(E_0 \sin\omega t + \alpha(E_0 \sin\omega t)^3 + \beta(E_0 \sin\omega t)^5 + \ldots)$$

$$= \varepsilon_0 \varepsilon_r \omega [(E_0 + 3/4\alpha E_0^3 + 5/8\beta E_0^5 + \ldots)\cos\omega t$$

$$+(-3/4\alpha E_0^3 - 5/16\beta E_0^5 + \ldots)\cos 3\omega t$$

$$+(5/16\beta E_0^5 + \ldots)\cos 5\omega t + \ldots]$$

hence the 3rd harmonic transfer function is given by:

$$IM_{H3} = 20\log\left|\frac{-3/4\alpha E_0^3 - 5/16\beta E_0^5 + \ldots}{E_0 + 3/4\alpha E_0^3 + 5/8\beta E_0^5 + \ldots}\right|$$

$$= 20\log\left(\frac{3}{4}\alpha E_0^2\right) \quad \textbf{(10)}$$

The value of α determines the level of non-linearity of each dielectric material and will vary from one material to another according to the operative mechanism. As an example to demonstrate this point, the experimental results, in Figure 5 and Table 1, show non-linearity in Nylon-66 and polythene to become significant at 700 V/mm and 2000 V/mm respectively. Hence non-linear permittivity is the likely mechanism. The polystyrene shows a much better performance and the most linear material is PTFE. Hence electrostriction is expected to be the main source of non-linearity. Good non-polar materials need much higher powers to excite significant non-linearity.

Table 1: 3rd harmonic level for the measured dielectric samples

Dielectric Material	Field strength (V/mm)	3rd harmonic Level(dBm)
Nylon-66	700	-106
Polythene	2000	-88
Polystyrene	2250	-94
Al. (AL_2O_3)	2250	not detected
PTFE	2250	not detected

5. Conclusion

These results demonstrate that care is needed in the use of dielectrics in any high field environment where 3rd harmonic must be kept to minimum. No measurements have been made on rutile loaded materials, but these can be expected to demonstrate significant non-linearity due to non-linear permittivity. It must also be appreciated that any trace of moisture will cause similar behaviour. This can be due to moisture absorption, which occurs to a varying extent, in most engineering dielectrics. Sample impurity is a farther factor and can cause significant degradation, particularly where good performance is important.

References

[1] A.Kumar "Passive IM Products Threaten High-Power Satcom Systems", Microwave & RF, Dec.1987, pp 98-103

[2] G.H.Stauss "Studies on the Reduction of Intermodulation Generation in Communication Systems" NRL Memorandum Report 4233, July 1980, pp 75-79

[3] C.J.F.Bottcher "Theory of Electric Polarization" Volume 1, Elsevier, Amsterdam, 1973, pp 318-323

[4] T. Nishikawa, Y.Ishikawa and J.Hattori "Measurement method of Intermodulation Distortion of Dielectric Resonator" Japanese Journal of applied physics 1988, pp 39-45

[5] A.P.Foord and A.D.Rawlins "A Study of Passive Intermodulation Interference in Space RF Hardware" ESA report, University of Kent, Electronic Eng. lab.,. 1992

[6] Burfoot, J.C., and Taylor "Polar Dielectrics and Their Applications" Macmillan Press, London, 1979

[7] Landau, L.D., and Lifshitz "Electrodynamics of Continuous Media" Pregamon Press, Oxford, 1984

[8] Smyth and C.P "Dielectric Behaviour and Structure" McGraw-Hill, New York, 1955.

[9] Zheludev and I.S. "Physics of Crystalline Dielectrics" Volume 2, Electrical Properties, Plenum Press, New York, 1971.

[10] Bogoroditskii, N.P., and Pasynkov "Radio and Electronic Materials" Iliffe Books, London, 1967

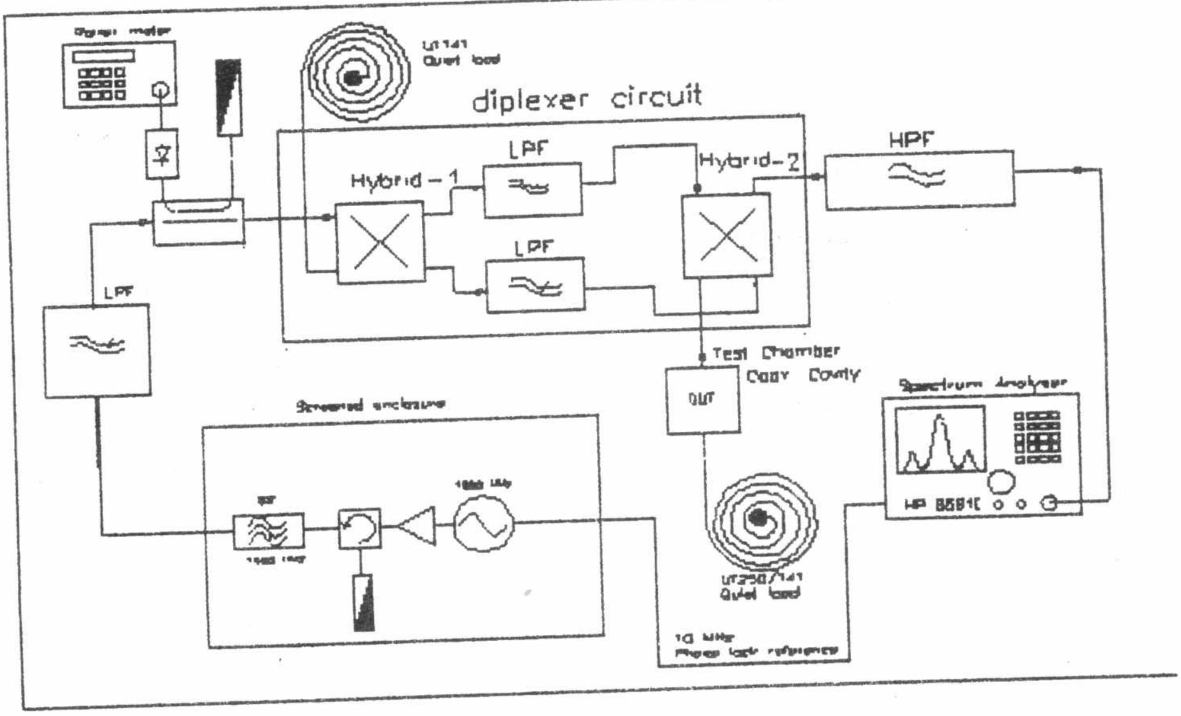

FIGURE 1. Measurement System Block Diagram

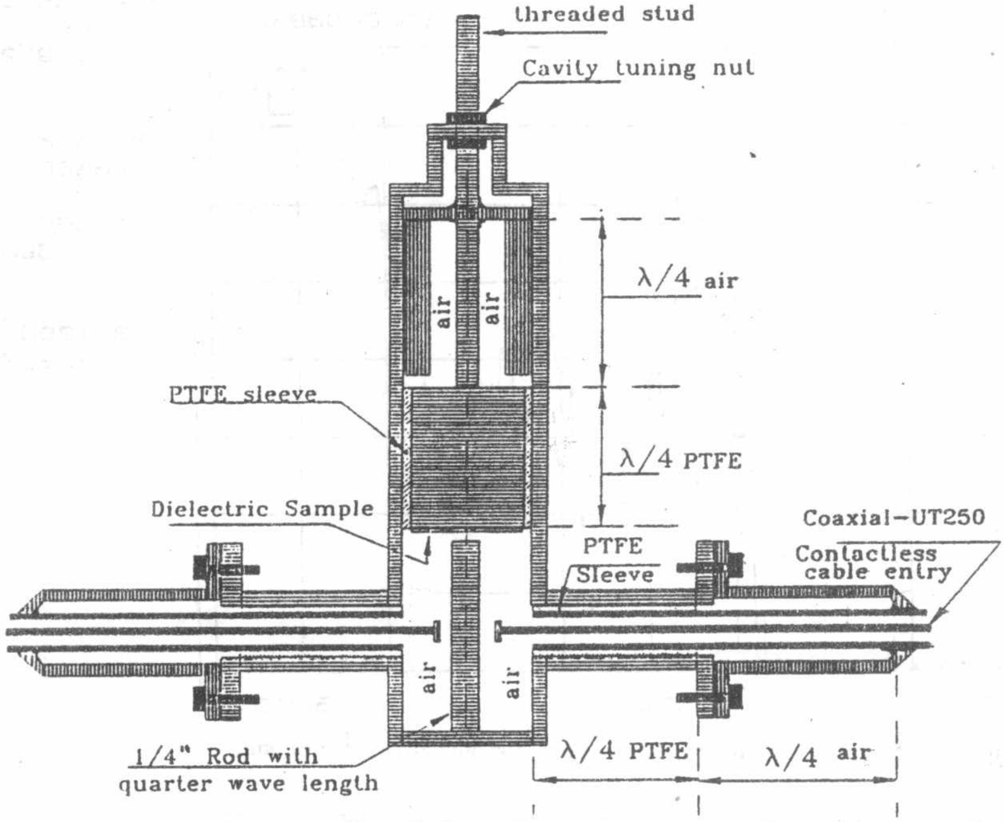

Figure 2. Test cavity structure

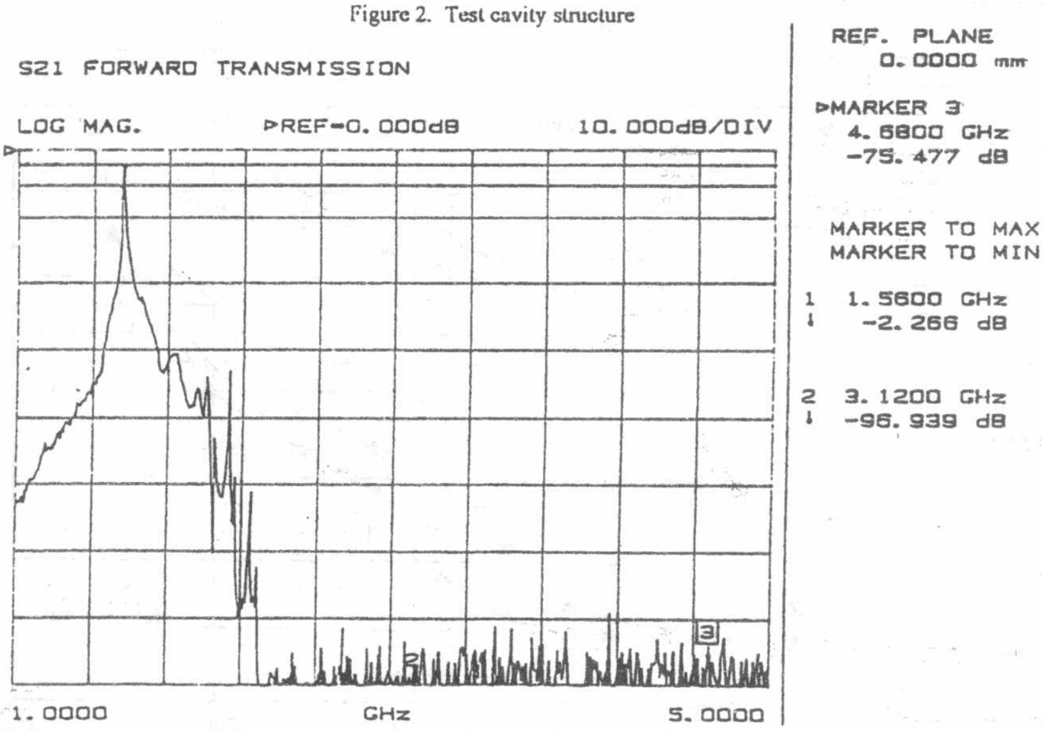

Figure 3. Measurement system performance in transmission mode

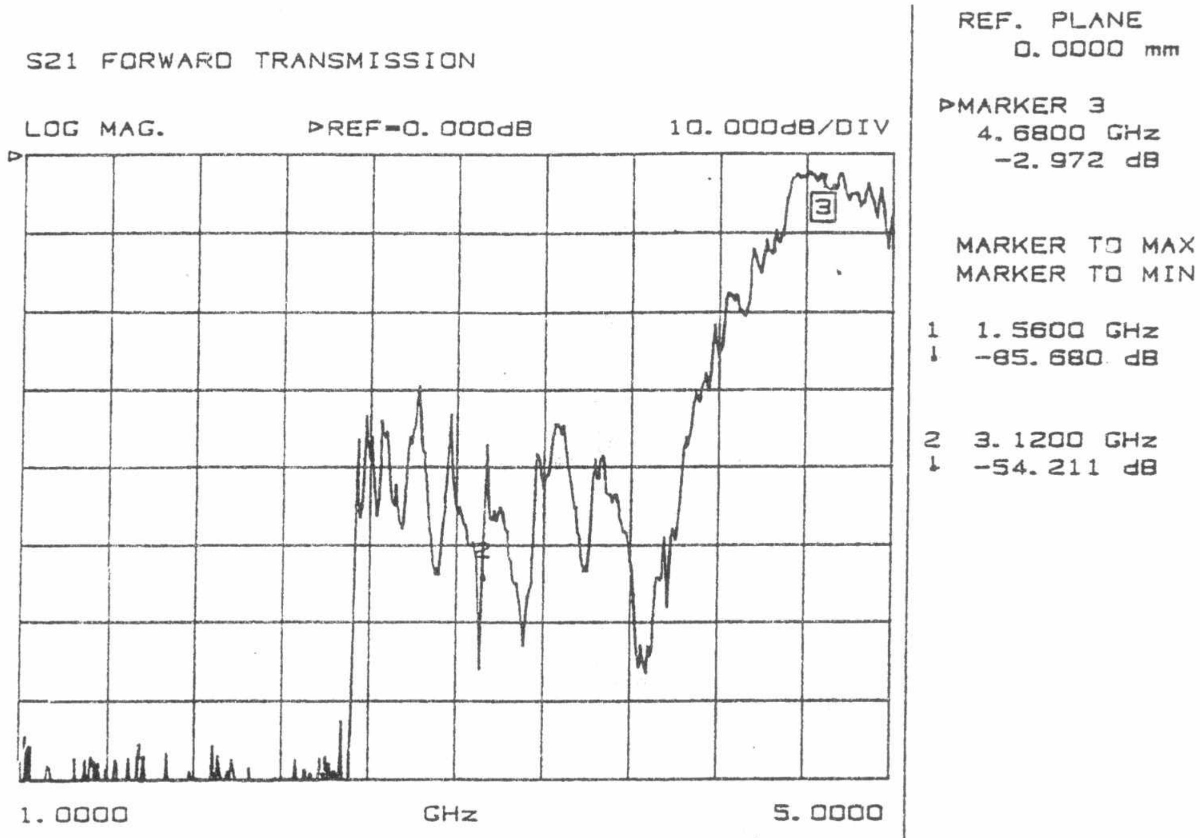

Figure 4. Measurement system performance for detecting 3rd harmonic

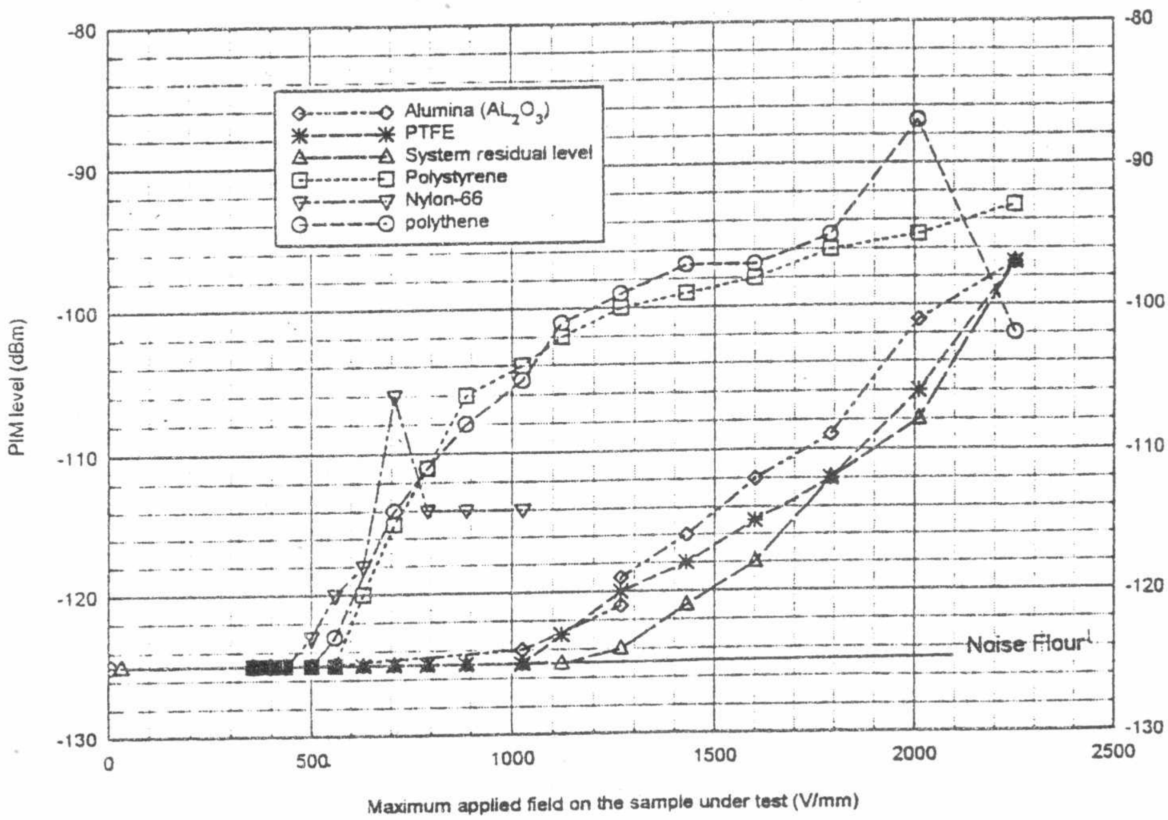

Figure 5. Measurement results