A STUDY OF SIGNIFICANCE OF METAMATERIALS ON PHYSICS AND ENGINEERING

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ABSTRACT— The metamaterials are artificially engineered structures with unusual electromagnetic properties. In this paper, we review the implementation of isotropic metamaterials that exhibit a negative permittivity and a negative permeability, thus leading to a negative index of refraction. Specifically, the paper focuses on transmission line metamaterials which are planar structures comprising a network of distributed transmission lines loaded periodically with inductors L capacitor C, in high pass configuration. The periodic unit cell is much smaller than the wavelength, thus leading to an effective medium in which the lumped loading elements can be either discrete or printed. Based on such negative – refractive – index transmission line metamaterials, several fundamental properties of physical sciences and engineering based microwave devices having broadband properties are explained.

Key words — Metamaterials, permittivity, permeability, composite materials, negative index material, negative refraction, lenses, microwave phase shifters, microwave broadband antenna and microwave balun.

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INTRODUCTION

The metamaterials are artificially engineered structures with unusual electromagnetic properties. The term metamaterials refers to artificial media with electromagnetic properties that transcend those of natural media (meta means beyond in Greek). Most researchers in this field restricts metamaterials to be artificially structured periodic media in which the periodicity is much less than the wavelength of the impinging electromagnetic wave. The scattering process can be macroscopically characterized by means of effective materials parameters, such as a permittivity, a permeability and a refractive index.

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To the best of our knowledge, the first attempt to explore the concept of artificial metamaterials appears to trace back to the let part of the 19th century when in 1898 Jagdish Chandra Bose [1] conducted the first microwave experiment on twisted structures, geometries that were essentially artificial chiral element by today's terminology. In 1914, Lindman [2] worked an "artificial" chiral media by embedding many randomly oriented small wire helices in a host medium. In 1948, Kock [3] made lightweight microwave lenses by arranging conducting spheres, disks and strips periodically and effectively tailoring the effective refractive index of the artificial media. Since, the artificial complex materials have been the subject of research for many investigators worldwide, so in recent years new concepts, in synthesis and novel fabrication techniques are employed. Fig.-1 given below is sketches of a volumetric metamaterial synthesized by embedding various inclusions in a host medium.
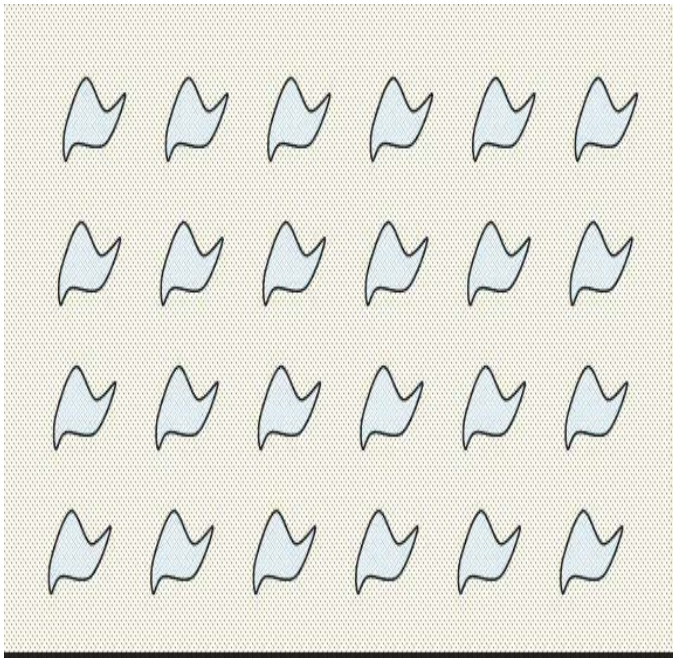
Fig.-1 : Generic sketch of a volumetric metamaterial synthesized by embedding various inclusions in a host medium.

In 1967, Veselago [4] theoretically investigated plane-wave propagation in a material whose permittivity and permeability were assumed to be simultaneously negative. Smith, Schultz [5, 6] and their group constructed such a composite medium for the microwave regime and demonstrated experimentally the presence of anomalous refraction in this medium.

Metamaterials are of different types :

(a)   SNG (Single negative metamaterial)

(b)   DNG (Double negative metamaterial)

(c)   EBG (Electromagnetic band gap metamaterial)

The SNG and DNG metamaterials involve inclusions and interinclusion distances that are much smaller than a wavelength and, as a consequence, such media can be described by homogenization and effective media concepts. On the other hand, the EBG metamaterials involve distances that are on the order of half a wavelength or more and are described by the Bragg reflection and other periodic media concepts.

This paper focuses on transmission line metamaterials, which are planar structures consisting network of distributed transmission lines loaded periodically inductor L capacitor C, in high pass configuration. The periodic unit cell is much smaller then the wavelength, thus loading to an effective medium in which the lumped loading elements can be either discrete or printed. Based on such negative refractive index transmission line metamaterials, several fundamental properties of physical sciences and engineering based microwave devices having broadband properties are explained.

Fundamental properties explaining physical sciences:

It is well known that the response of a system to the presence of an electromagnetic field is determined to a large extent by the properties of the materials involved. We describe these properties by defining the macroscopic parameters permittivity $\in$ and permeability μ of these materials. This allows for the classification of a medium as follows. A medium with both permittivity and permeability greater than zero ($\in > 0$, $\mu > 0$) will be designated a double-positive (DPS) medium.

Most naturally occurring media fall under this designation. A medium with permittivity less than zero and permeability greater than zero ($\in < 0$, $\mu > 0$) will be

designated an epsilon-negative (ENG) medium. In certain frequency regimes many plasmas exhibit this characteristic. For example, noble metals behave in this manner in the infrared (IR) and visible frequency domains. A medium with the permittivity greater than zero and permeability less than zero ($\in > 0$, $\mu < 0$) will be designated a mu-negative (MNG) medium. In certain frequency regimes some gyrotropic materials exhibit this characteristic. Artificial materials have been constructed that also have DPS, ENG, and MNG properties. A medium with both the permittivity and permeability less than zero ($\in < 0$, $\mu < 0$) will be designated a DNG medium. To date, this class of materials has only been demonstrated with artificial constructs. This medium classification can be graphically illustrated as shown in Fig.-2.
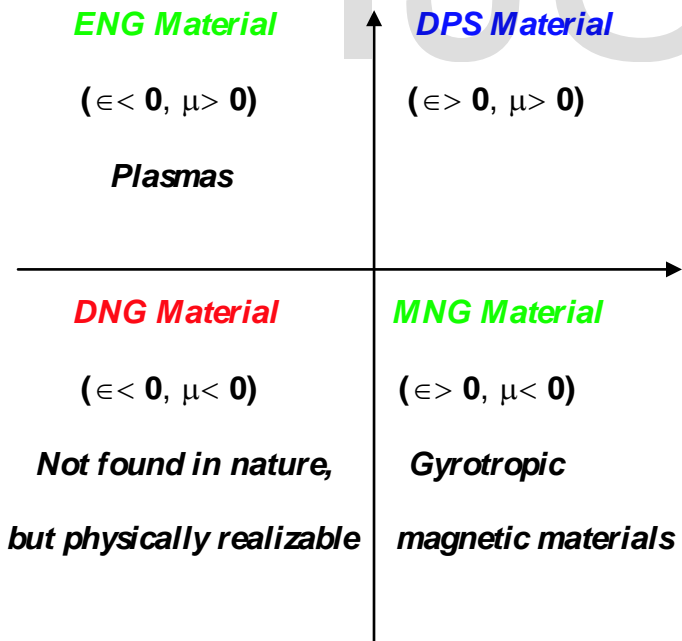
ENG Material

($\in < 0$, $\mu > 0$)

Plasmas

DPS Material

($\in > 0$, $\mu > 0$)

DNG Material

($\in < 0$, $\mu < 0$)

Not found in nature, but physically realizable

MNG Material

($\in > 0$, $\mu < 0$)

Gyrotropic magnetic materials

Fig. –2 : Material classifications.

The reflection and transmission coefficients associated with a normally incident plane wave that scatters from a DNG slab embedded in a medium have been derived. The geometry is shown in Fig.-3.
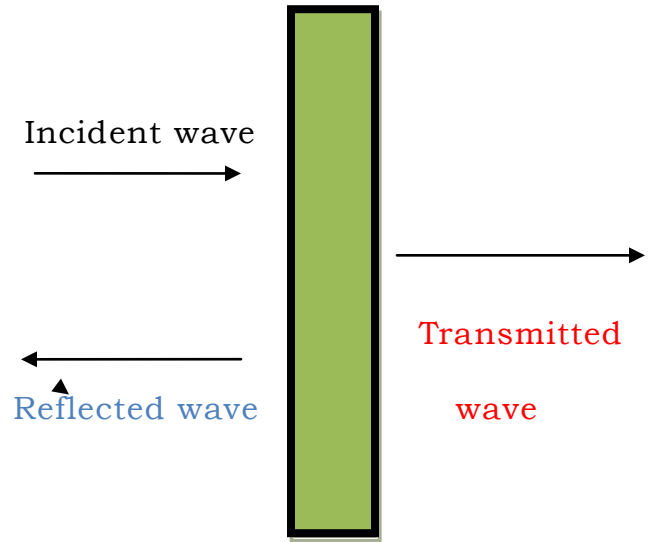

Fig. –3 : Plane-wave scattering from slab of thickness d.

The slab has an infinite extent in the transverse directions; it has a thickness d in the direction of propagation of the incident plane wave. Let the medium before and after the slab be characterized by $\in 1$, $\mu 1$ and the slab be characterized by $\in 2$, $\mu 2$. For a normally incident plane wave, the reflection and transmission coefficients for the slab are

$$R = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \frac{1 - e^{-j2k_2d}}{1 - \left[(\eta_2 - \eta_1)/(\eta_2 + \eta_1)\right]^2 e^{-j2k_2d}}$$

$$T = \frac{4\eta_2\eta_1}{(\eta_2 + \eta_1)^2} \frac{e^{-jk_2d}}{1 - \left[(\eta_2 - \eta_1)/(\eta_2 + \eta_1)\right]^2 e^{-j2k_2d}}$$

$$\dots \ (1)$$

where the wave number $k_i = \omega\sqrt{\in_i}\sqrt{\mu_i}$ and wave impedance $\eta_i = \sqrt{\mu_i}/\sqrt{\in_i}$ for i = 1, 2. For the case of

normal incidence, if we consider a matched DNG medium, one would have η2 = η1 so that R = 0 and T =

$$e^{-jk_2d} = e^{+j|k_2|d}$$.

Negative refraction :

The phenomenon of negative refraction is studied by considering the scattering of a wave that is obliquely incident on a DPS–DNG interface as shown in Fig.-4.
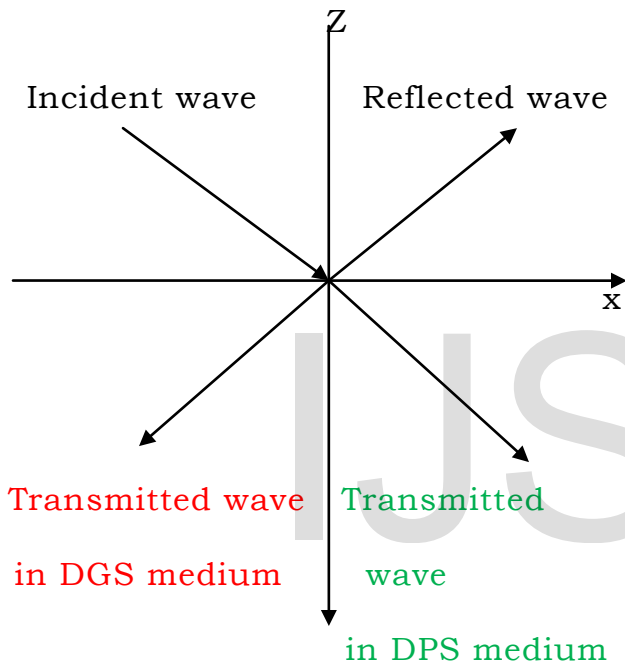

Fig.–4 : Geometry of the scattering of a wave obliquely incident upon a DPS-DNG interface.

Enforcing the electromagnetic boundary conditions at the interface, one obtains the law of reflection and Snell's Law from phase matching :

$$\theta reff = \theta inc \quad \& \quad \theta trans = \text{sgn}\,(n2)\,\sin^{-1}\left(\frac{n_1}{|n_2|}\sin\theta_{inc}\right)$$

…(2)

Note that if the index of refraction of a medium is negative, then the refracted angle, according to Snell's law, should

also become "negative". This suggests that the refraction is anomalous, and the refracted angle is on the same side of the interface normal as the incident angle is. The wave and Poynting vectors associated with this oblique scattering problem are also obtained :

$$k_{inc} = k_1\left(\cos\theta_{inc}\,\hat{z} + \sin\theta_{inc}\,\hat{x}\right)$$

$$k_{reff} = k_1\left(-\cos\theta_{inc}\,\hat{z} + \sin\theta_{inc}\,\hat{x}\right)$$

…(3)

$$k_{trans} = k_2\left(\cos\theta_{trans}\,\hat{z} + \sin\theta_{trans}\,\hat{x}\right)$$

Microscopic and Macroscopic views of Metamaterials :

The substances postulated in [7] have not yet been found in nature and need to be fabricated in the laboratory. Currently, they are realized as an arrangement of metallizations properly oriented in space, yielding metamaterials that are therefore intrinsically inhomogeneous and microscopic. On the other hand, the metallizations themselves as well as their separations are very small compared to the operating wavelength. Calling upon the effective medium theory, it is therefore legitimate to look for bulk properties, in this case a bulk permittivity and permeability, that govern the macroscopic behavior of the medium.

These two views, the microscopic view on one hand and the macroscopic view on the other, are two aspects of the same problem that are connected by retrieval algorithm which, from a set of parameters measured on the microscopic metamaterials, yield the bulk properties of the macroscopic metamaterials. Various retrieval algorithms

have been published in the literature [8–10], all with the same purpose of establishing the connection between the metallizations and the constitutive parameters of the effective medium. In the next section, we shall briefly describe both points of view to ascertain how these metamaterials are realized and how they are modeled.

Microscopic View : Rods and Rings as Building Blocks of Metamaterials:

Current implementations of metamaterials rely on 'infinite" rods and split-ring resonators (SRRs) to achieve a negative permittivity and a negative permeability, respectively. The rings can take various shapes, some of which will be detailed in the forthcoming sections. The rings are the building blocks to achieve an effective frequency-dispersive permeability, which has been shown to obey the frequency dispersive Lorentz model [3] illustrated in Fig.- 5a,b.

$$\mu_r = 1 - \frac{f_{mp}^2 - f_{mo}^2}{f^2 - f_{mo}^2 + iY_m f / 2\pi}$$

…(4)

where the subscript r refers to relative values, Ym is the magnetic damping factor, and fmo and fmp are the magnetic resonant and plasma frequencies, respectively, with fmo < fmp. It is seen that for frequencies between fmo and fmp the permeability assumes negative values. The shape of the rings, their effective radii, the width of their metallizations, and many other factors directly translate into their properties and govern their resonant and plasma frequencies, which are directly related to the bandwidth

where negative values occur. Hence, it is of little surprise that the design and optimization of the geometry of the rings have been an active area of research.
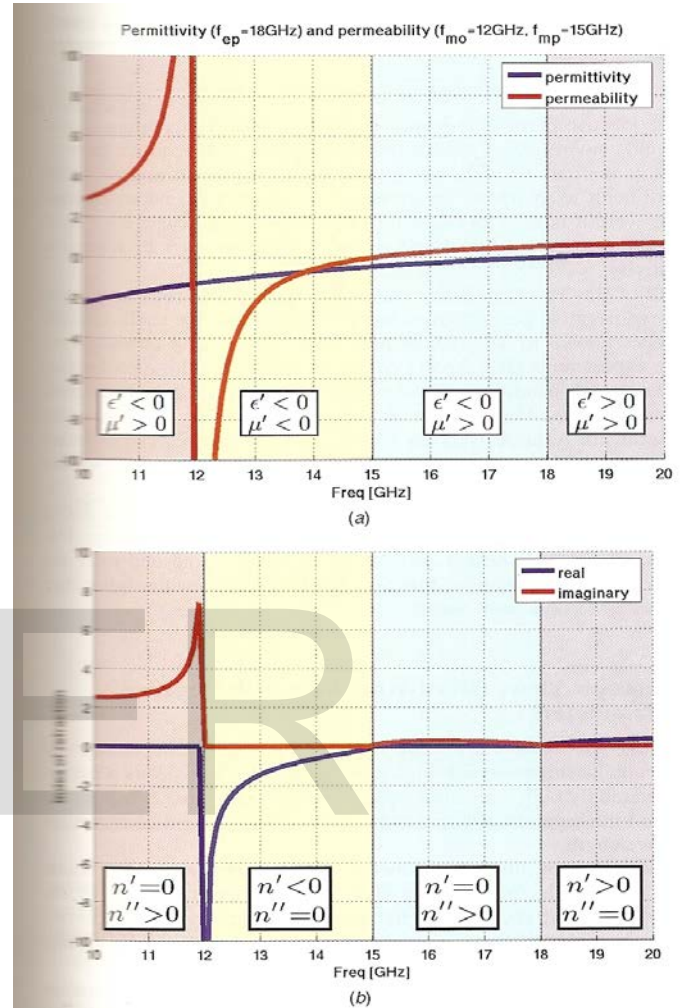

Fig. – 5a,b : Permittivity, permeability, and associated isotropic index of refraction for a medium characterized by a Drude model and a Lorentz model.

Properties on Engineering :

In conventional positive-refractive-index (PRI) transmission-lines (TLs), the phase lags in the direction of positive group velocity, implying that the phase incurred is negative. It therefore follows that phase compensation can be achieved at a given frequency by cascading a section of a

negative-refractive-index line (i.e., a backward-wave line) with a section of a positive – refractive-index line to synthesize positive, negative, or zero transmission phase at a short physical length.

The structure of Fig.-6 can be rearranged to form a series of symmetric metamaterial unit cells, as proposed in [11,12]. Such a unit cell is shown in Fig.- 7. It is nothing but a transmission line of characteristic impedance Z0, periodically loaded with series capacitors C0 and shunt inductors L0. A representative dispersion diagram for typical host transmission-line and loading parameters is shown in Fig.- 8.

Fig.–8 : The dispersion diagram for the periodic structure with typical line and loading parameters. The edges of the stop band are designated by fc1 and fc2.
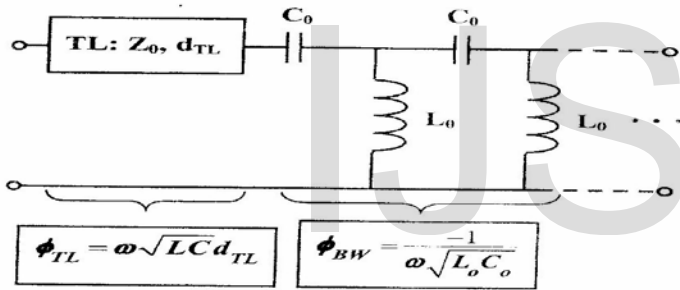

Fig.-6 : A phase-compensating structure based on a conventional transmission line and a backward-wave line.
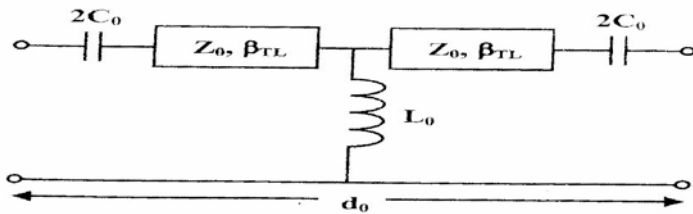

Fig.–7 : A unit cell of a metamaterial phase-shifting line comprising a host transmission-line, periodically loaded with series capacitors and shunt inductors.
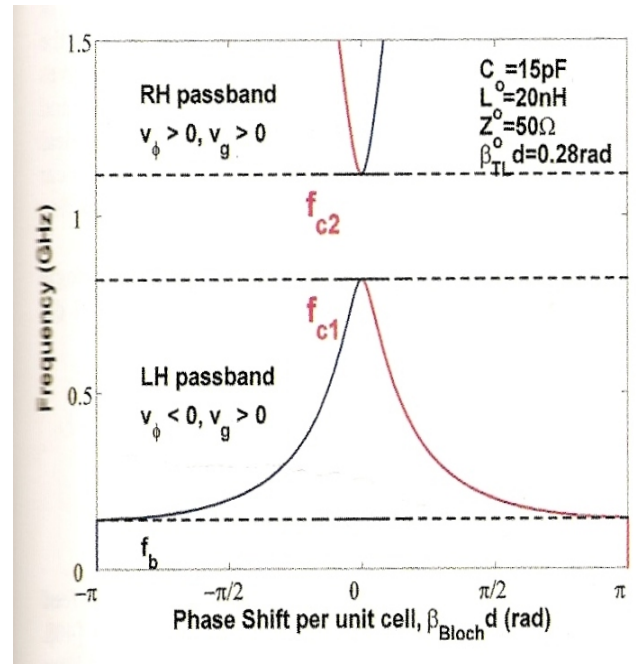
The metamaterial phase-shifting lines can then be constructed by cascading a series of these unit cells. The edges of the stop band, fc1 and fc2 in Fig.-8 are determined at the series resonance between the inductance of the transmission line section and the loading capacitor, CO, and the shunt resonance between the capacitance of the transmission-line section and the loading inductance, L0, respectively. Alternatively, these are the frequencies at which the effective permeability, $\mu N (\omega)$, and the effective permittivity, $\in N(\omega)$, vanish : $\in N(\omega) = 0$, $\mu N (\omega) = 0$.

Broadband Balun :

Baluns are particularly useful; devices for feeding two-wire antennas, where balanced currents on each

branch are necessary to maintain symmetrical radiation patterns with a given polarization. Two-wire antennas have input ports that are closely spaced, therefore, their feeding structures should be chosen to accommodate this requirement. A broadband NRI-TL balun that meets these requirements is shown in Fig.–9a and 9b.
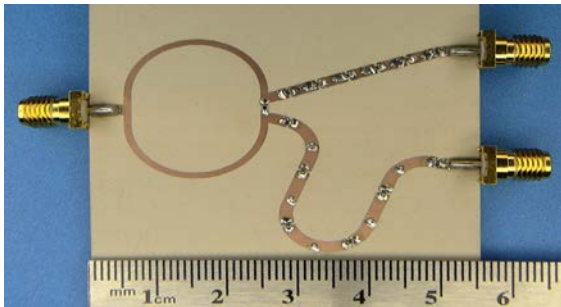

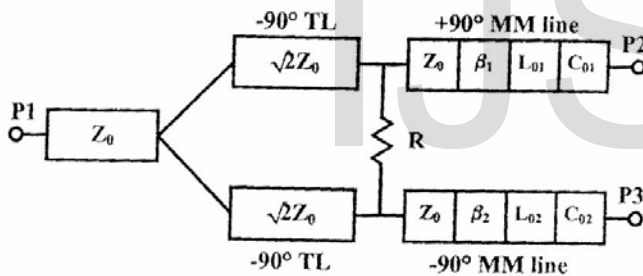Fig.-9a : A photograph of the fabricated NRI-TL balun in microstrip.

Fig. –9b : The architecture of the NRI-TL balun.

It consists of a Wilkinson power divider, followed by a +900 metamaterial phase-shifting line along the bottom branch.

Fig.- 10a shows excellent isolation for the device, as well as an equal power split between the two output ports. Fig.-10b shows the measured and simulated differential output phase of the NRI-TL balun, with excellent agreement between the two. It can be observed that the differential output phase remains flat for a wide frequency

band, which follows directly from the fact that the phase characteristics of the +900 and –900 lines match very closely. The flat differential output phase has a 1800 ± 100 bandwidth of 1.16 GHz, from 1.17 GHz to 2.33 GHz. For comparison, a distributed-transmission-line Wilkinson balun (TL-balun), employing –2700 and –900 lines instead of the +900 and –900 metamaterial lines, was also simulated, fabricated, and measured at f0 = 1.5 GHz. The differential output phase of the transmission-line balun is also shown in Fig.- 10b. It can be observed that the phase response of the transmission-line balun was linear with frequency, with a slope equal to the difference between the phase slopes of the –2700 and –900 transmission lines.
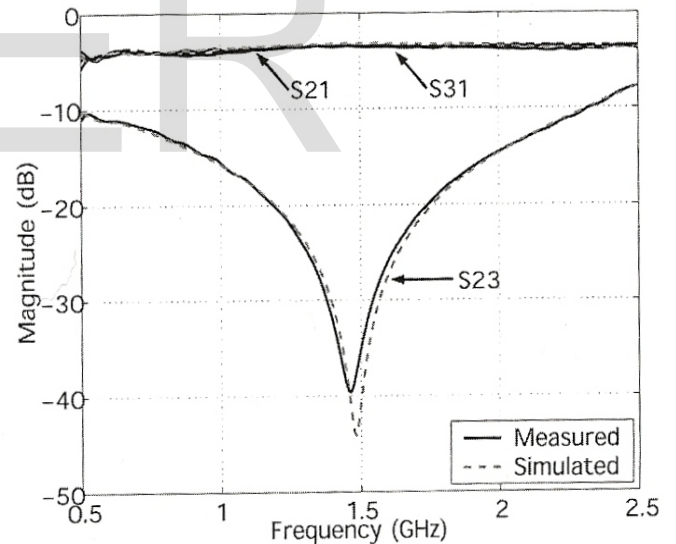

Fig.-10a : The measured and simulated isolation (S23) and through (S21 and S31) magnitude responses of the NRI-TL balun.
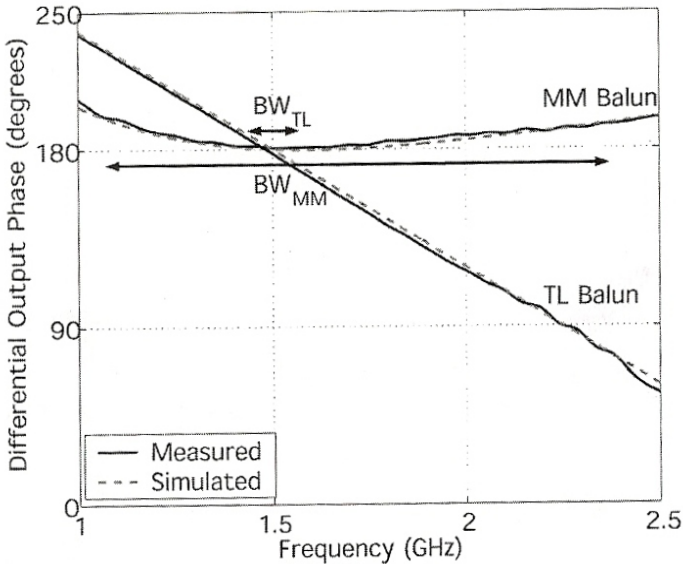
Fig.-10b: The measured and simulated differential phase comparison between the NRI-TL balun and the transmission line balun.

Since the gradient of the resulting phase characteristic was quite steep, this rendered the output differential phase response of the transmission-line balun narrowband. Thus the transmission-line balun exhibited a measured differential phase bandwidth of only 11%, from 1.42 GHz to 1.58 GHz, compared to 77% exhibited by the NRI-TL balun. In addition, the transmission-line balun occupied an area of 33.5 cm2, compared to 18.5 cm2 for the NRI-TL balun. Thus, the NRI-TL balun was more compact, occupying only 55% of the area that the conventional transmission-line balun occupied. Furthermore, the NRI-TL

balun exhibited more than double the bandwidth, compared to a lumped element implementation using low-pass/high-pass lines, which typically exhibited a bandwidth of 32% [13]. This can be attributed to the fact that the low-pass line has a linear phase response, while the response of the high-pass line has a varying slope with frequency. Thus, the shapes of the phase responses of the two lines did not match resulting in a more narrowband differential output phase.

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