Microwave integrated circuits on a ferrite substrate

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Introduction

In addition to passive components, like filters and couplers, and active elements such as semiconductor oscillators, many microwave systems use non-reciprocal elements. They are called non-reciprocal because their characteristics depend on the direction in which the signals propagate in them. For example, propagation is strongly attenuated in one direction but weakly attenuated in the other, so that the non-reciprocal element passes the signals in one direction only. Such devices may be used for one-way couplings between generator and load to prevent the load from reacting upon the generator (isolators), or in radars for separating transmitting and receiving systems connected to a common aerial (circulators). Recently non-reciprocal devices have also come into use as variable phase-shifters for controlling directional aerials without the use of mechanical systems ("phased arrays").

These non-reciprocal microwave elements are based on a magnetic material; in practice a special class of ferrite is used. This ferrite possesses ferrimagnetic properties; it is given a magnetic anisotropy by an external static magnetic field. The anisotropy is used for producing the non-reciprocal effect.

The operation of the ferrite components is controlled by means of the external magnetic field, for both analog and digital applications. In digital use the external field serves only to reverse the remanent magnetization of the ferrite, with the significant advantage that no holding power is needed in the time between reversals. Other interesting microwave applications of ferrites result from using the non-linear effects in these materials, for example in the construction of power limiters.

In introducing microwave integrated circuits into microstrip technology [1] it is also necessary to consider non-reciprocal or non-linear ferrite devices in planar miniaturized form. The ferrite can be used as the substrate material for the microstrip circuit, the ferrite element then being an integral part of the microwave transmission line. This is a practical possibility since polycrystalline sintered ferrite substrates have outstandingly good electrical and mechanical properties. The magnetic and dielectric losses are low, and the mechanical density of the material is so high that optically polished surfaces can be produced. Both these features contribute towards low propagation losses in a microstrip system.

Ferrite can also be used as a non-ferrimagnetic material. By making appropriate chemical substitution the Curie point (below which the material is ferrimagnetic) can be shifted to low temperatures, so that in the working temperature range the material is a pure dielectric that can be generally applied as a high-quality substrate. In the laboratory it has also been found possible to sinter magnetically active zones into the non-magnetic ferrite substrate. This gives in one operation a "composite substrate" on which a microstrip circuit with reciprocal and non-reciprocal elements can be produced in a single photo-etching process [2].

Ferrimagnetic and non-magnetic substrates are made in our laboratories. Their use underlies the investigations on microstrip components and subsystems described in this article. Before going on to examine a number of typical non-reciprocal devices we shall first take a closer look at wave propagation in a ferrite medium. The explanation of non-reciprocity is to be found in the interaction between the r.f. magnetic field and the electron spins in ferrimagnetic ferrite.

Wave propagation in ferrites

An electromagnetic wave is able to propagate in ferrites of the type considered here because, unlike other magnetic materials, they are insulators in which no eddy currents can occur, and because their magnetic and dielectric losses are low (magnetic loss factor tan $\delta_H \leq 10^{-6}$, electric loss factor tan $\delta_e \leq 2 \times 10^{-4}$).

When a ferrite is magnetized to saturation by applying a static magnetic field, the elementary magnetic moments, i.e. the electron spins responsible for the magnetism of the material, are oriented parallel to the magnetic field. If they are deflected from this parallel orientation, for example by an r.f. magnetic field normal...
mal to the static field, the electron spins do not simply assume the instantaneous direction of the resulting field but precess around the direction of the static field (Fig. 1) [3]. The angular frequency $\omega$ of the precession is given uniquely by the local magnetic field $H$:

$$\omega = 2\pi y H; y = 35.2 \text{ kHz A}^{-1}\text{m} (= 2.80 \text{ MHz Oe}^{-1}).$$

In this way an electromagnetic wave propagating in a magnetized ferrite medium can interact with the electron spins. This is most clearly seen for a circularly polarized wave, which has a rotating magnetic field vector. When this vector rotates in the same direction as the precessing spins the interaction with the ferrite medium is strong. When the vector rotates in the opposite direction the interaction is weak. In each case the wave has a different phase velocity and attenuation. It follows from this that the interaction between the ferrite medium and a microwave signal is dependent on the direction of propagation of the wave; the propagation is non-reciprocal.

In practice non-reciprocal microstrip components are frequently made by exciting a circular r.f. magnetic field in a waveguide arrangement, so as to obtain the maximum coupling to the ferrite. However, it is also possible to produce a non-reciprocal device (e.g. the field-displacement isolator shown in Fig. 3a) in which the electron spins are excited by a linearly polarized r.f. magnetic field. It becomes clear that a linearly polarized field will also interact with the electron spins if this kind of field is considered as the sum of two circularly polarized components, one right-handed (clockwise) and the other left-handed (anti-clockwise). New magnetic-field components arise because of the precession of the electrons, and these cause the field to lose its original linear polarization. The propagation can then be made non-reciprocal in an asymmetric waveguide structure.

At high r.f. fields there are non-linear effects. These arise because the cone of precession becomes wider, and give extra losses. Such effects are made use of in limiters.

**Microstrip components on a ferrimagnetic ferrite substrate**

**Circulator**

Microstrip circulators for frequencies between 3 GHz and 18 GHz have been studied in our laboratories. Purely ferrimagnetic substrates have been used as well as sintered composite substrates, and gave comparable results. Fig. 2a shows a typical circulator for 16 GHz. Three ports are coupled to a circular metal disc which acts as a resonator. The disc rests on a ferrimagnetic ferrite substrate magnetized in a direction perpendicular to the surface by a permanent magnet. This non-reciprocal device always allows energy to be transferred from input 1 to 2, from 2 to 3 and from 3 to 1, but not in the reverse direction. Thus, if we connect 1 to a transmitter, 2 to an aerial and 3 to a receiver, the transmitted signal will go only to the aerial and the incoming signal only to the receiver. In this configuration the circulator permits the same aerial to be used for transmitting and receiving. The sensitive receiver is protected from the transmitter power by the circulator. A good circulator should therefore combine maximum isolation in one direction with minimum attenuation (insertion loss) in the other. Typical curves of isolation $a_{1-3}$ and insertion loss $a_{1-2}$ plotted against frequency are shown in Fig. 2b. The isolation curve has the characteristic shape of a resonance curve. The bandwidth is primarily determined by the coupling of the circulator ports to the resonator. Given appropriate coupling the reflections at the circulator disc are weak, as appears from the small standing-wave ratio (the voltage standing-wave ratio $S$ is smaller than 1.2 at the centre frequency [4]).

The operation of this type of circulator depends on the dissimilarity in the wavelengths of the waves circulating clockwise and anti-clockwise along the circumference of the circular disc. A standing-wave field is set

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**Fig. 1. A spinning electron (angular momentum $b$, magnetic moment $m$) precessing in a magnetic field $H$. The magnetic field attempts to align the magnetic axis of the electron parallel to the field and exerts on the electron a couple that in every infinitesimal time interval adds a small increment $\Delta b$ to the angular momentum $b$. Under the influence of the field the apex of the vector $b$ describes a circle around the direction of the magnetic field; $\Delta b$ is always tangential to this circle. A spinning top precesses in a similar way because of the effect of the gravitational field.**
A circulator for 16 GHz. Three microstrip lines are coupled to a resonator in the form of a circular disc. The circuit is mounted on a ferrimagnetic ferrite substrate, which is magnetized in a direction perpendicular to the surface by a permanent magnet. Energy transfer is only possible from input 1 to 2, from 2 to 3 and from 3 to 1. b) Insertion loss ($\alpha_{1\rightarrow2}$), isolation ($\alpha_{1\rightarrow3}$) and voltage standing-wave ratio ($S$) as a function of the frequency $f$.

Isolator

An isolator passes the signal in one direction and absorbs it in the other. The reaction of the load upon the generator can therefore be removed without appreciably attenuating the useful signal. In some applications, an isolator can be produced from a circulator by using port 1 as the input, port 2 as the output and terminating port 3 in a matched load. Planar thin-film matched loads have been developed in microstrip, and these will be discussed below.

Another type of isolator is shown in fig. 3a. Here again the static magnetic field is perpendicular to the

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[4] Whenever signals are reflected at a discontinuity in the transmission path, they interfere with the oncoming signals to form standing waves, and a stationary voltage pattern with maxima and minima at alternate quarter-wavelengths is set up on the transmission line. The ratio of the maximum and the minimum voltage is called the voltage standing-wave ratio ($S$). If the signal is totally reflected the minimum voltage is zero and consequently $S = \infty$; if there is no reflection at all no maxima and minima occur and $S = 1$. In matching a microwave element to a circuit, $S$ is usually made as close to unity as possible.
surface of the substrate. On the substrate there is a microstrip line that is considerably broadened out to one side, half-way between the connectors; the added part of the width overlaps an area of vacuum-evaporated nickel chromium. In this field-displacement isolator the microwave signal is conducted, depending on the direction, either along one edge of the stripline to the output, or along the other edge to be absorbed by ohmic losses in the nickel-chromium film [6]. Since an isolator of this type does not include any form of transmission-line resonator it is essentially a broad-band device. Measurements on an isolator designed for 12-18 GHz are given in fig. 3b. The isolation was higher than 40 dB for a bandwidth of 2 GHz and more than 30 dB over the whole frequency band at a static magnetic field of 0.52 tesla (5200 gauss). The insertion loss in the transmission direction was always less than 1.5 dB. The good match evident from the small voltage-standoff ratio (S ≈ 1.23), in conjunction with the large bandwidth, would make this type of isolator eminently suitable for applications in microwave measurement techniques using a swept frequency, and in other broad-band systems.

**Phase-shifters**

A typical non-reciprocal microstrip phase-shifter on a ferrite substrate is shown in fig. 4. On the substrate there is a microstrip “meander line” (fig. 4a) in which the loops are a quarter wavelength long (\(\lambda/4\)); the distance between them is comparable with or smaller than the substrate thickness. Consequently the lines of force of the r.f. magnetic fields of neighbouring strips intersect each other in the substrate approximately at right angles (fig. 4b); at the centre of the strips the phase difference is 90°. This implies that the r.f. field in this region is circularly polarized. With static magnetization normal to the plane of the picture in fig. 4b there is non-reciprocal interaction with the electron spins. This static magnetization is applied by means of a wire or a few turns through the hole in the centre of the ferrite substrate. The change in the phase velocity of the microwave signal on this structure depends on the magnitude of the applied magnetic field. This type of device can therefore be used as a magnetically tunable phase-shifter.

If a square-loop ferrite is used in the system shown in fig. 4 a digital phase-shifter is obtained. Saturation switching of the toroidal ferrite is effected by a wire through the hole in the toroid. Use is made of the difference in phase shift between the two opposite remanence points of the magnetization curve (“latching device”). Groups of such digital phase-shifters can be used in phased arrays for radar [8]. The figure of merit of these devices is the maximum phase shift per dB loss. We have achieved values of about 200°/dB at 9 GHz.

**Microstrip components on non-ferrimagnetic ferrite substrates**

**Passive components**

The propagation of microwave signals on microstrip and slotline with non-ferrimagnetic ferrite substrate is similar to that on alumina-based transmission lines, as described in a previous article [1]. We shall give an account of some measurements on ferrite-based microstrip and slotline and compare the results with calculations based on a theory of these lines that has been developed at our laboratories [7]. This theory includes the dispersion in microstrip at higher frequencies; this has been neglected in earlier theories [8]. The higher dispersion of slotline is also calculated. The results are given in fig. 5a and b, which show the relative wavelength \(\lambda/\lambda_0\) as a function of frequency \(\lambda\) is the wave-
Fig. 5. Measurements and calculations of wavelength and propagation losses for a microstrip line and a slotline made on a non-ferrimagnetic ferrite substrate. The calculations for the microstrip line are based on a theory that takes into account the dispersion ensuing from the deviations from TEM waves. a) The wavelength $\lambda$ on the microstrip line, divided by the wavelength $\lambda_0$ in free space, as a function of frequency. H. A. Wheeler’s theory \([8]\) assuming TEM waves yields a frequency-independent value of $\lambda / \lambda_0 = 0.359$. b) The quantity $\lambda / \lambda_0$ for the slotline. Calculated values are represented by the curve. c) Losses over one wavelength $\alpha \lambda$ measured for microstrip line (dots) and slotline (circles).

The small systematic deviations in absolute value between theory and experimental data are due to an inaccurate determination of the dielectric constant $\varepsilon_r$. Losses for transmission lines on the non-magnetic ferrite substrate are of the same order of magnitude as on the alumina substrate, since the magnetic loss factor $\tan \delta_m$ (see page 315) does not apply here (see fig. 5c).

The impedance of the microstrip transmission line is essentially determined by the thickness and dielectric constant of the substrate and the width of the conducting strip. In microstrip on a ferrite substrate the characteristic impedance is restricted to the range from about 20 to 100 ohms. Lower impedance values are not acceptable because they would require strip widths which would no longer be small compared with the wavelength, so that the transmission-line characteristics would be lost. The upper impedance limit is set by the increasing losses of extremely narrow lines.

Numerous microstrip components have been developed by combining sections of transmission line. Two band-pass filters and a 50-ohm termination will now be discussed in more detail.

The two filters are shown in fig. 6; they are designed

![Fig. 6](image-url)
for maximally flat response at frequencies between 8 and 12 GHz. The filter shown in fig. 6a is formed from a series of $\lambda/2$ stubs with $\lambda/4$ separation along the main transmission line. Since high stub admittances are not feasible, the minimum bandwidth of this filter is about 10%. A second type of filter is shown in fig. 6b. It consists of a number of parallel coupled $\lambda/2$ resonators, five of them in the case shown. Here the minimum bandwidth is determined by the microstrip losses, i.e. by the maximum $Q$-factor of a linear resonator. A $Q$ of about 300 can be obtained, corresponding to a bandwidth of about 3%.

To produce a matched load, there has to be a gradual transition between the loss-free transmission line and an attenuating system. In the spiral load (fig. 7) a gradual increase in the absorption is achieved by a gradual transformation of the microstrip mode into even and odd modes propagating between adjacent turns of the conducting spiral. The electric-field vector of the odd mode lies in the surface of the substrate and is attenuated in the thin nickel-chromium film evaporated on to the spiral. The accuracy of the match can be deduced from the voltage standing-wave ratio ($S$): typical values for 50-ohm terminations are shown in fig. 7.

**Subsystems**

As examples of microstrip subsystems made on a non-magnetic ferrite substrate we shall now discuss a microstrip Gunn oscillator and a balanced mixer using beam-lead diodes. Conventionally a Gunn oscillator for a fixed frequency is used with a microstrip resonator $\lambda/2$ long. An improved version of a microstrip oscillator for 9.2 GHz is shown in fig. 8 and experimental results are shown in fig. 9. This type of oscillator has two circular resonators of the same resonant frequency. The resonant frequency of a circular resonator is determined by the diameter of the metal disc and the dielectric constant of the substrate. The diameter of the disc on the right in fig. 8, which contains the Gunn element, is slightly decreased to compensate for the reactance of the Gunn device. The $Q$ of this resonator is relatively low and the frequency stability of the system is determined by the left-hand resonator ($Q \approx 400$) coupled directly to the first disc. The oscillator is more stable and has a narrower linewidth than an oscillator with $\lambda/2$ resonator (fig. 9).

A microstrip balanced mixer designed for a centre frequency of 11.5 GHz is shown in fig. 10. This mixer was developed for future television reception in the 12 GHz band. The local-oscillator and signal frequencies are combined in the hybrid ring (which is of a different design from the one shown in a previous article but operates on similar principles) and fed to the two Schottky-barrier diodes $D^{[12]}$. These non-encapsulated diodes (beam-lead diodes) are incorporated in the mixer structure by thermocompression bonding. As can be seen from fig. 10, the distance between the diodes and the hybrid is different, the difference in path-length is $\lambda/4$. This introduces an additional 180° phase shift for the signal reflected at one of the diodes. Because of this phase shift the signals reflected at the diodes add up in such a way that they return entirely to the signal input, and the local-oscillator signals reflected at the diodes return to the local-oscillator input.
This permits both these inputs to be matched externally to the mixer circuit and provides more than 20 dB of isolation between them for a 10% bandwidth. The measured noise figure is shown in fig. 11. It does not seem possible to achieve much lower values than those shown here. These values would be too high for the direct reception of satellite-based television transmitters, and additional pre-amplification would be required. The noise figure is however low enough for application of the mixer as the first stage of a television receiver for terrestrial transmitters on 12 GHz.

These two examples show that microwave integrated circuits of high quality can be made on a substrate of non-ferrimagnetic ferrite. Ferrite thus appears to be an all-round substrate material: it is indispensable for non-reciprocal elements, and in the non-magnetic form it is of great value for general application.

Summary. In many microwave systems non-reciprocal elements are used (circulators and isolators). These non-reciprocal devices can be produced in the form of integrated circuits using microstrip on a substrate of ferrimagnetic ferrite. When an external magnetic field is applied the wave propagation in the ferrite becomes non-reciprocal, owing to the interaction of the r.f. magnetic field with the precession of the electron spins around the external magnetic field. The article describes a circulator, a broad-band isolator and a meander-line phase-shifter. By chemical substitution the Curie temperature of the ferrite can be reduced to below the working temperature. The ferrite is then a very suitable general substrate material for microstrip circuits with a high dielectric constant ($\approx 12$) and low loss factor ($<2 \times 10^{-4}$). Some filters, a 50-ohm matched load, a Gunn oscillator and a low-noise mixer are described. If the circuit contains a non-reciprocal element a ferrimagnetic zone can be sintered in, producing a composite substrate.

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[12] The silicon Schottky-barrier diodes were supplied by Dr. D. de Nobel of Philips Research Laboratories, Eindhoven.