II-7. A Two-Port Microwave Variable Delay Line

F. A. Olson and L. D. Buchmiller

Microwave Electronics Corp., Palo Alto, Calif.

The ability to delay microwave signals and, in particular, to electronically control the delay, is exceedingly important in certain electronic systems. There has been considerable activity in this field recently, much of it centered about fixed-delay techniques using acoustic waves, and variable-delay techniques using combinations of acoustic waves and spin waves, in various single-crystal materials. This paper describes the operation of a new kind of delay device—a two-port electronically variable delay line utilizing pure spin-wave propagation in single-crystal yttrium iron garnet. Particular advantages of this device are transmission-type (two-port) operation, delay continuously variable from zero to several microseconds by means of the magnetic field, and no critical dimensions or surface finishes.

The small magnetic loss in yttrium iron garnet (YIG) allows reasonably efficient generation and propagation of magnetostatic waves and spin waves. In the development described here, the magnetic waves result from a transverse microwave magnetic field applied to a small portion of a YIG sample, such as the end region of a longitudinally magnetized rod. The magnetic disturbance propagates through the crystal in the form of magnetic waves and, because the medium is dispersive, the velocity of the waves can be varied by changing the applied dc magnetic field.

The propagation characteristics of magnetostatic and spin waves in a ferrimagnetic crystal have been calculated for various geometries and various magnetic field magnitudes and orientations. The method of calculation, an approximate technique, is similar to that giving the resonant modes of a microwave cavity and the results are of the same form as those from the more involved calculations of Fletcher and Kittel.[1]

In the approximate calculation, it is assumed that a magnetic wave produces periodic variation of the magnetization in planes perpendicular to the direction of propagation so that periodic magnetic poles are formed; hence, there are changes in the effective length of the sample. The effective rf demagnetizing factors are found using these effective lengths, and the resonant modes are calculated from the usual ferromagnetic resonance formula. The magnetic modes are assumed to form a continuum which represents the dispersion characteristic of the transmission system. The slope of the dispersion curve (the group velocity) is a function of the operating point and becomes very small in the short-wavelength portion of the curve. Thus, by varying the operating point by means of the magnetic field, the wave velocity can be changed over a large range to provide continuously variable delay.

The propagation of magnetic waves was observed in an experimental structure such as that shown in Fig. 1. Thin-wire extensions of the coaxial center conductors serve as rf couplers. The magnetic field produced by these couplers is transverse to the applied dc field. Rod-shaped samples of single-crystal YIG were used as the transmission medium. A variety of sam-

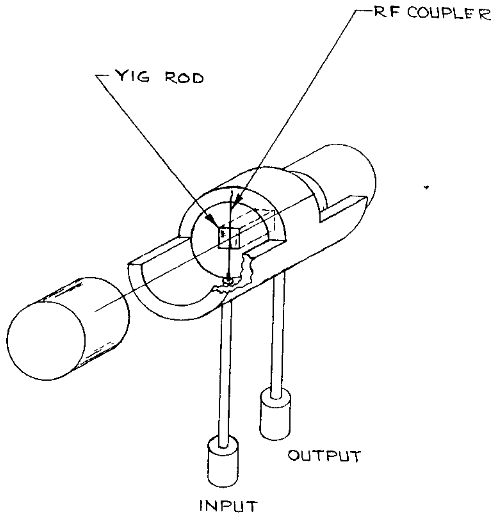

Fig. 1 Structure for generation and propagation of magnetic waves in YIG to provide microwave variable delay (H_{dc} applied parallel to rod axis).

ples were tested—rectangular and circular cross sections, orientations along the [100], [110], and [111] axes, polished and unpolished end faces. The entire structure was placed in a steady, uniform external magnetic field parallel to the rod axis, and magnetic mode propagation was observed for all samples.

The signal transmitted through the YIG rod could be delayed from zero to several microseconds by increasing the applied magnetic field. Small changes in field change the wave velocity from $\sim 10^9$ cm/sec to $\sim 10^5$ cm/sec; thus, the effective bandwidth of operation is relatively narrow. Figure 2 is a multiple exposure oscilloscope picture showing the increase in delay of an L-band signal as the magnetic field is increased. An input level of -30 dbm and a pulse length of 3 microseconds were used in this example. The variable delay has been observed at frequencies as low as 1 Gc and as high as 10 Gc, with pulses from one to several microseconds in width.

A graph of the magnetic field required for two microseconds of delay is shown in Fig. 3 as a function of frequency. Also shown in Fig. 3 is the theoretical result of dispersion curve calculations. The agreement between theory and experiment is good.

The insertion loss of the delay line is greater than 40 db for the initial experimental test structures. It is believed that much of the 40 db is made up of coupling loss and, hence, can be drastically improved. The insertion loss increases with delay at the rate of approximately 3 db per microsecond in the lower microwave frequency range. This corresponds to a magnetic relaxation time of $\tau \approx 10^{-6}$ seconds, which correlates with measurements of the relaxation of the uniform precession and of spin waves of low k number in YIG. Further correlation of the loss measurements comes from the qualitative agreement of the rate of increase of propagation loss with frequency. Thus, as the coupling efficiency of the variable delay device is improved, the ultimate insertion loss, which is determined by the intrinsic loss of the magnetic system, can become small.

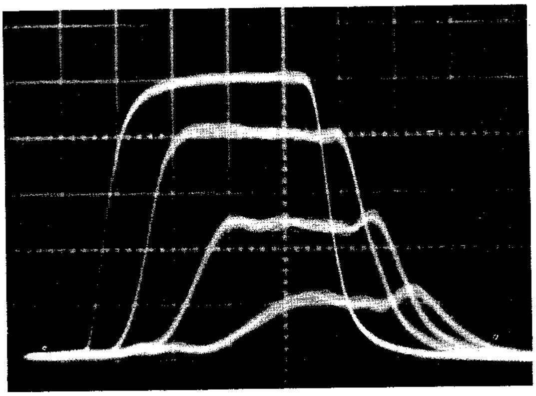

Fig. 2 Multiple exposure oscilloscope picture showing the delay of a 3 microsecond pulse as a function of magnetic field (frequency = 1.4 Gc; vertical scale = 10 v/cm; horizontal scale = 1 μsec/cm).

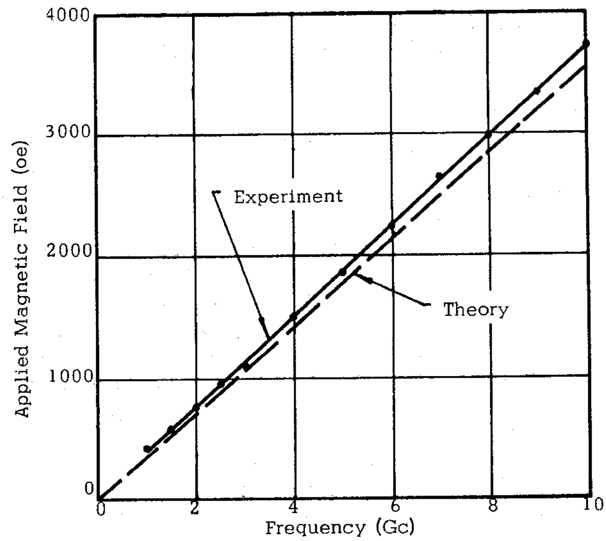

Fig. 3 Magnetic field required for a two microsecond delay as a function of frequency.

The development of this variable delay process, utilizing spin wave propagation, is one of three forms of delay that have been observed using YIG in the microwave frequency range. They are:

1. Acoustic wave propagation, with essentially fixed delay and requiring precisely aligned and polished end surfaces.

2. Spin-wave/acoustic-wave propagation, giving delay which is variable from one to several microseconds with magnetic field, but which also re-requires polished end surfaces and operates as a reflection device.

3. Spin-wave propagation, giving delay which is continuously variable from zero to several microseconds with magnetic field, unaffected by end conditions, and is a transmission device.

The acoustic-wave propagation was first reported by Spencer, *et al*,[2] and the spin-wave/acoustic-wave propagation by Eshbach,[3] and by Strauss.[4] Each of the three forms of delay has been observed at frequencies from 1 Gc to 10 Gc in the rod-like samples used in these experiments. A comparison of the performance of these delay processes, with particular attention to insertion loss, bandwidth, frequency limits, and variable delay range, will be presented. The relative advantages over more conventional microwave delay lines, such as size, weight, and delay duration, will also be described, along with the performance improvements expected for solid state variable-delay devices.

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