VIII-5 TWO-PORT UHF PULSE COMPRESSION VIA MAGNETOSTATIC WAVES IN YIG RODS

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I. Introduction

Dispersive spin wave modes in low-loss single crystals of yttrium-iron-garnet (YIG) have been recognized for some time as candidates for microwave "matched filter" devices with pulse compression applications. In assessing magnetostatic modes for these applications, comparison with magnetoelastic modes in unavoidable. Recently, magnetoelastic pulse compression experiments have been carried out by several investigators[1,2,3]. Although wide bandwidths and prospects for linear delay dispersion are evident, there are several delicate problems which must be satisfactorily resolved in any practical device, including magnetoelastic defocusing effects, amplitude fluctuations, satisfactory two-port configurations which take full advantage of the available bandwidths, and the onset of low-level spin-wave nonlinearities. Conceding advantages of bandwidth and delay dispersion linearity to the magnetoelastic mode, magnetostatic dispersive lines may well be highly satisfactory where these considerations are not of prime importance.

Magnetostatic lines are not sensitive to crystal orientation, they do not require optical-tolerance surface finishes, they appear to have substantially higher nonlinearity thresholds, and the longer wavelengths involved should make low loss rod-to-rod coupling feasible when required without the need for delicate optical bonding techniques. In addition, bandwidths in the tens of MHz appear feasible and a broadband coupling efficiency of ~ 11 db/coupler is currently observed in the UHF range.

II. Magnetostatic Delay Dispersion

The observation of magnetostatic volume modes in axially magnetized YIG rods was first reported in 1964[4], and a quantitative analysis of the time delay based on the Fletcher-Kittel dispersion relation[5]

$$\frac{f}{\gamma} - H_i = 2\pi M\left(\frac{2.405}{kR}\right)^2 \qquad (1)$$

and the Sommerfeld demagnetizing field appeared in 1966[6]. Although Eqn. 1 applies to a uniformly magnetized rod immersed in a dielectric environment, one can show that in the same magnetostatic approximation this relation is unchanged when the rod is conductively clad. Hence Eqn. 1 is an appropriate basis for most magnetostatic experiments. From this relation, the magnetostatic transmission delay is given by

$$T = 0.270\frac{\sqrt{f_M}(L/2R)}{\Delta f\left[\Delta f + \gamma H_2(L/2)^2\right]^{\frac{1}{2}}}, \qquad (2)$$

where Figure 1 assists in the definition of terms. The quadratic coefficient in the Taylor series expansion of the internal axial field (H_i) is H_2 (oe/cm^2), and H_o is the actual axial field value at rod center. Note the relations $\Delta f = \gamma\Delta H$ and $f_M = \gamma 4\pi M$, with $\gamma = 2.8 \times 10^6$ (oe-sec)$^{-1}$.

Figure 1 also indicates the character of Eqn. 2 for a range of the dispersion-determining product H_2R^2. Noting that $\partial T/\partial f = -T/\Delta f$ or $-3T/2\Delta f$, according to whether Δf is much smaller or larger than $\gamma H_2(L/2)^2$, the conditions for high or low dispersion are apparent and consistent with the sketch in Figure 1. If minimum dispersion is sought in the interests of wide bandwidth and moderate delay, then one seeks to flatten the internal field profile and operate under the condition $\Delta f \gg \gamma H_2(L/2)^2$. Then from Eqn. 2,

$$T \approx 19.0 \times 10^3 \; (L/2R) \; \Delta f^{-3/2} \qquad (3)$$

for YIG. To indicate the dispersion linearity which is possible, Figure 2 displays Eqn. 3 in normalized form. The broken line is an empirical straight line from which the actual delay curve deviates equally at the band edges, and approximately midband. The linearity, defined as the maximum deviation divided by the total delay range, is approximately 10%. Thus Eqn. 3 indicates that a YIG rod with $L/2R = 20$ can provide a 1 to 0.35 microsecond delay variation with 10% linearity in a 52.5 MHz bandwidth. On the basis of linear pulse compression analysis[7] this represents a 19 nanosecond compressed pulse and a compression ratio of about 34. The same linearity is available for a 2 to 0.7 microsecond delay variation with 33 MHz bandwidth, yielding a 30 nanosecond compressed pulse and compression ratio of about 43. Wider bandwidths and larger compression ratios are available at the expense of delay dispersion linearity.

If high delay dispersion is sought by increasing H_2R and by requiring $\Delta f \ll \gamma H_2(L/2)^2$, the validity limits of Eqn. 2 are quickly exceeded. This is a result of radial variation in the axial magnetic field. Laplace's equation relates the axial and radial behaviour of the magnetic potential[8] such that the axial field, when expanded about the rod center, is given by

$$H_i = H_o - H_2 z^2 + H_2 r^2/2 \; , \qquad (4)$$

It seems apparent that analytical difficulty will be encountered when ΔH is reduced to a value comparable to the variation in axial field from rod center to rod surface, $H_2R^2/2$. In particular the outer surface of the rod becomes cut off, according to Eqn. 1, when $\Delta H < H_2R^2/2$. The magnetostatic delay anticipated on the basis of Eqn. 2, when $\Delta H = GH_2R^2/2$, is given by ($\Delta H \ll H_2L^2/4$):

$$T_m = 0.294 \; \frac{(1 + A^2)^{15/4}}{G \, f_M \, A^{3/2}} \; , \qquad (5)$$

where H_2 has been calculated from the Sommerfeld expression for the natural demagnetizing field in a saturated rod, and $A = L/2R$. With $G = 1$, T_m might be interpreted as the maximum delay for which Eqn. 2 is applicable. For most practical values of A, T_m is proportional to A^6. When $A = 5$, $T_m \approx 0.94$ microseconds. This may explain why previous magnetostatic delay measurements have only been in qualitative agreement with Eqn. 2.

III. Experimental Delay Dispersion

In order to provide sounder evidence for the validity of Eqn. 2 than has been published to date, 800 MHz delay measurements were performed with 1 microsecond pulses on a <111> YIG rod (.928" long, .140" x .145" rectangular cross section, Xtalonics Products, Inc.) in which the field profile had been artificially flattened with axial magnetic shunts. Conventional fine wire excitation was employed. Changes in ΔH were effected by varying the applied field, but arguments can be made that resultant changes in the rod internal field profile are not likely to be important. Long delay data were used to determine the ΔH origin and the value of

H_2, based on the assumption $\Delta H << H_2 (L/2)^2$. With this information, the whole range of data and Eqn. 2 (taking R = .071") were plotted in Figure 3. The agreement is excellent.

From the data the following parameters are determined: $H_2R^2/2 \approx 0.08$ oe, $H_2(L/2)^2 \approx 7$ oe, $H_2 \approx 4.8$ oe/cm^2. Since $\Delta H >> H_2R^2/2$ in the measurements, the departures from theory at long delays are attributed strictly to measurement errors caused by the great dispersion present (when T = 5 microseconds, $|\partial T/\partial f| \approx 0.9$ microseconds/MHz).

Propagation losses over most of the range of Figure 3 were 5.3 db/μsec, comparing favorably with the 6 db/μsec number extrapolated from Strauss' 1.6-8.5 GHz determination of spin wave lifetimes[9].

IV. Pulse Compression Filter

Figure 4 displays a YIG magnetostatic pulse compression filter package with permanent magnet and a container of magnetic shielding alloy. The dispersion characteristic is tunable from 400-750 MHz, as indicated in Figure 5. The coupling loss is ~11 db/coupler over the frequency band, and the propagation losses are in the 6-7 db/microsecond range. Nonlinearities in the filter response are not evident until an input power of ~50 mw is reached.

This filter was tested at 500 MHz with a flat-topped 4-microsecond pulse bearing 10 MHz modulation, tailored very crudely to complement the measured dispersion curve. With the magnetic field optimally adjusted, Figure 6 was obtained on a sampling oscilloscope. This indicates a compressed output pulse approximately 0.2 microseconds wide with one prominent sidelobe 6 db down. The main pulse is 15 db down from the Chirp input. The absence of amplitude tailoring in the input pulse implies that substantial frequency information is being preferentially absorbed in the lossy filter.

V. Conclusions

UHF magnetostatic pulse compression in YIG rods may be summarized as follows:

- YIG selection and preparation is simple, as is the filter construction.
- The entire device including magnets and some degree of magnetic shielding may be contained in an 8 oz. package.
- The delay dispersion characteristic is magnetically tunable over nearly an octave.
- The dispersion characteristic is neither linear nor possessed of odd symmetry, thus precluding passive Chirp generation techniques.
- Delay losses of 6-7 db/microsecond prevent practical delays of more than several microseconds.
- Two-port coupling losses in a magnetically tunable device are approximately 22 db.
- High dispersion tends to limit compression ratios to less than 100, unless drastic dispersion nonlinearity is tolerable.
- Bandwidths of several tens of MHz with 10% dispersion linearity appear possible.

In conclusion, dispersive magnetostatic modes in YIG rods provide an attractive approach to microwave pulse compression for applications not requiring high dispersion linearity or bandwidths in excess of 50-100 MHz.

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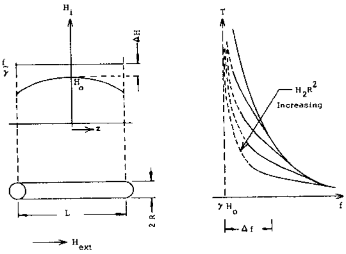

FIG. 1 - Magnetostatic propagation.
Left: Definition of terms.
Right: Characteristic delay dispersion

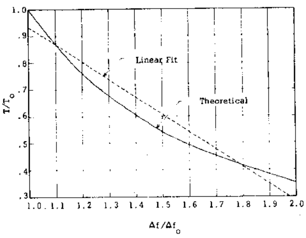

FIG. 2 - Normalized magnetostatic delay dispersion

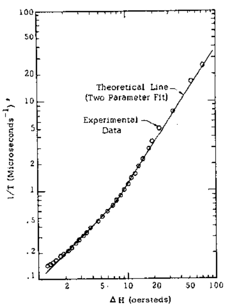

FIG. 3 - Magnetostatic delay dispersion at 800 MHz

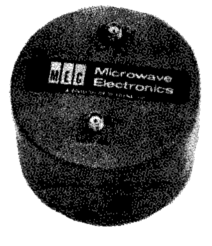

FIG. 4 - UHF Pulse Compression Fitter

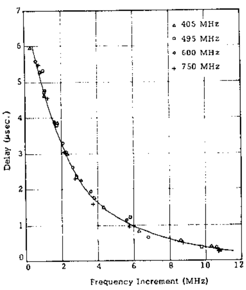

FIG. 5 - Filter delay dispersion

FIG. 6 - 500 MHz Pulsed Compression 1 usec/cm.
Bottom Trace: "Chirp" Input Signal, 10 MHz
Modulation. Top Trace: Compressed Pulse, 15 db down