and it is independent of δ, i.e., independent of the coupling iris. Expressing the guide wavelength of (5) in terms of resonant and cutoff frequencies, and after simple algebraic manipulations, the cutoff frequency of the waveguide is expressed as follows:

$$f_c^2 = f_q^2 - [A/4 + (f_q^2 - f_0^2)/A]^2 \quad (6)$$

where $A = qc/d$, and $c = 2.99792 \times 10^8$ meters/s.

It should be noted that the accuracy of (6) depends on the measurement of the resonant frequencies f_q and f_0. For long sections of waveguide, two adjacent resonant frequencies ($q=1$) are so close together that commercial wave meters cannot give accurate resolution. It is suggested, therefore, that investigations be performed on relatively short sections and that q be taken greater than one.

A 2.996-inch K-band (WR-42) waveguide section was shorted on both ends with a $\frac{1}{8}$-inch coupling hole made at the center of one end plate. The cavity has six resonant frequencies in this band, with the first and the sixth resonances occurring at 18.341 Gc/s and 25.798 Gc/s, respectively. The cutoff frequency calculated by (6) is 14.053 Gc/s (with $q=5$), with accuracy up to five significant figures, compared with the exact value 14.051 Gc/s. The value of the difference $\delta_q - \delta_0$ is in the order of 10^{-6}, and the magnitude of δ is about 0.032. The average of six cutoff frequencies each calculated for a measured resonant frequency by the phase constant method is 14.014 Gc/s. One reason for the discrepancy is due to not taking δ into account.

To demonstrate the fact that the cutoff frequency measurement is independent of the coupling hole, a vertical slit was cut in the short. The first and sixth resonant frequencies were 18.348 Gc/s and 25.810 Gc/s, respectively, and the cutoff frequency was 14.047 Gc/s which is only 6 Mc/s less than the first calculation.

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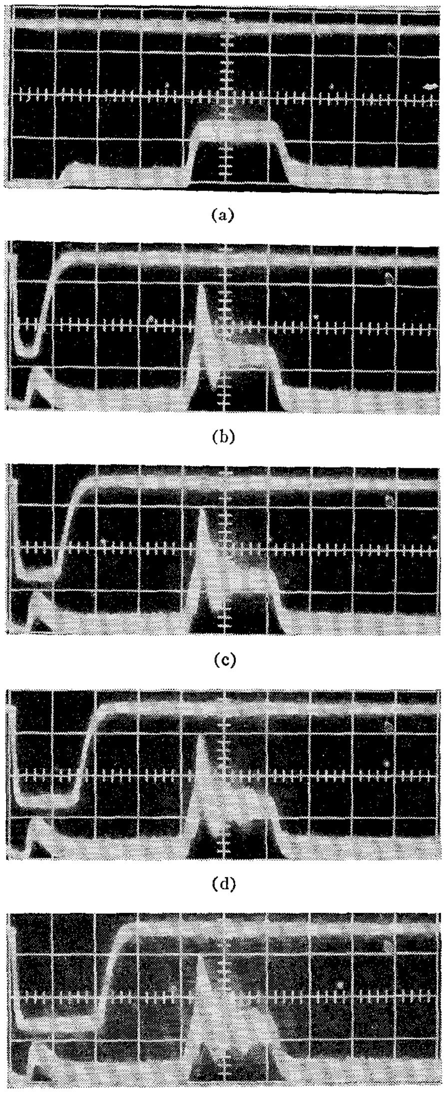

Fig. 1. Oscilloscope photographs showing independence of transient gain on pump pulse width. Upper trace in each photo is video detected pump pulse. Lower traces: signal frequency 1 Gc/s; pump frequency 2 Gc/s; input signal level 13 dBm; pump power 1.5 watt peak; signal pulse width 2 μs; pump, pulse width (a) pump off, (b) 0.5 μs, (c) 1.0 μs, (d) 1.5 μs, (e) 2.0 μs, horizontal time 1 μs/cm, dc magnetic field 1200 Gauss.

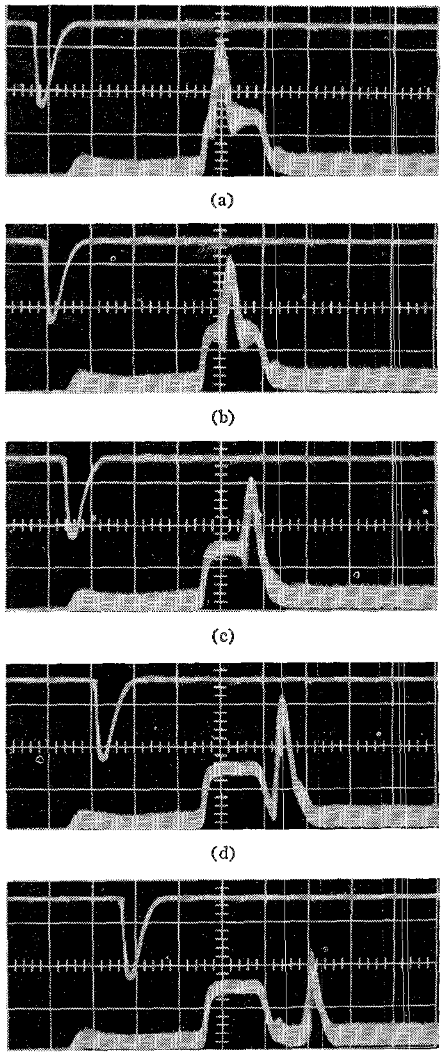

Fig. 3. Selective amplification over the range of the signal pulse duration. Upper trace in each photo is video detected pump pulse. Lower traces: signal frequency 1 Gc/s; pump frequency 2 Gc/s; input signal level 13 dBm; pump power 1.5-watt peak; signal pulse width 1.5 μs; pump pulse width 0.5 μs; horizontal time 1 μs/cm; dc magnetic field 1200 Gauss.

Characteristics of Transient Parametric Amplification of Elastic Waves in YIG

The observation of a transient mode of quasi-degenerate parametric amplification of elastic waves in YIG was reported[1] in an earlier letter along with other modes of operation. The purpose of this correspondence is to describe further experiments that have been conducted in order to characterize in greater detail the very high gain, transient amplification process in the microwave frequency range.

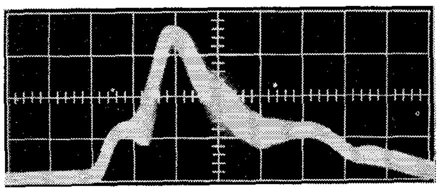

Fig. 2. Expanded view of transient gain phenomenon. Signal frequency 1 Gc/s; pump frequency 2 Gc/s; input signal level 13 dBm; pump power 1.5-watt peak; signal pulse width 2 μs; pump pulse width 1 μs; dc magnetic field 1200 Gauss; horizontal time base 0.4 μs/cm.

As in the previously reported measurements, thin wire excitation was used at both ends of the [111] oriented YIG crystal bar that measured 1.48 cm in length and 0.33 cm on each side. All of the data was taken by observing the reflected pulses at the signal input end of the bar. The signal frequency was maintained at 1 Gc/s and the pump frequency held constant at approximately 2 Gc/s. For an RF signal input level of -13 dBm and a magnetic bias field aligned parallel to the bar axis of 1200 Gauss, three elastic wave pulses were detectable with no pump power applied. The pulses were separated in time by an interval corresponding to the velocity of propagation[2] of transverse elastic waves in YIG.

With the signal pulse width maintained constant at 2 μs, the series of oscilloscope photographs shown in Fig. 1 was taken. In Fig. 1(a) the pump frequency was turned off, and in Fig. 1(b) through (e) the pump frequency was turned on with pulse widths

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[1] R. A. Sparks, and E. L. Higgins, "CW pumped and nondegenerate parametric amplification of elastic waves in YIG," *Appl. Phys. Letters*, vol. 7, pp. 41–43, July 15, 1965.

[2] A. E. Clark and R. E. Strakna, "Elastic constants of Single-Crystal YIG," *J. Appl. Phys.*, vol. 32, pp. 1172–1173, June 1961.

ranging from 0.5 to 2.0 μs. The turn-on time of the pump was adjusted so that its leading edge corresponded smoothly with the leading edge of the signal pulse. The pump power was held constant at 1.5-watts peak for all cases. It will be noted that regardless of the pump pulse width the parametric coupling apparently occurs only during the initial turn-on time of the pump.

The character of the leading and trailing edges of this "spike gain" phenomenon can be seen more clearly in the expanded oscilloscope photograph shown in Fig. 2. Although the true response time of the magnetoelastic interaction process is probably masked by the relatively narrow-band (10 Mc/s) IF amplifier employed in the experimental arrangement, the observed transient suggests a very rapid initial buildup, followed by an exponential relaxation. Noise fluctuations on the tail of the decay inhibited any detailed observations of a ringing effect, which is suggested by the slight undershoot in the amplified pulses of Fig. 1.

It should also be pointed out that by using a suitably narrow signal pulse, the amplification can be made to take place for the entire pulse duration. As can be seen from Fig. 2, the width of the amplified portion of the signal pulse at the half-power points is about 0.5 μs. If superimposed on a signal pulse less than 1-μs wide, amplification effectively occurs over the entire pulse. Amplification of elastic waves by means of the "spike gain" phenomenon have resulted in electronic gains of 55 dB at room temperature, thus far.

One further experiment that was performed is illustrated by the series of oscilloscope photos shown in Fig. 3. In this case, the pump pulse width was held constant at 0.5 μs and the pump turn-on time, as represented by the upper trace in each photo, was smoothly varied across the width of the signal pulse. In Fig. 3(a) the leading edge of the pump pulse corresponds with the leading edge of the signal pulse. Figures 3(b), (c), and (d) select out successively later portions of the signal pulse including the trailing edge. Finally, in Fig. 3(e) only the elastic wave noise pulse[3] is visible in the absence of any interaction with a coherent signal.

This latter experiment demonstrates the feasibility of achieving a coherent variable delay that is electronically controllable through the turn-on time of the pump. By maintaining the input signal power just below the output level of detectability, the leading edge of the pump pulse might be used as a sensitive probe to raise the desired portion of the signal pulse out of the noise level. It is to be noted that the process described differs from the variable time delay of microwave pulse echoes reported by Damon and van de Vaart[4] for spin waves.

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[3] H. Matthews, "Elastic wave amplification in yttrium iron garnet at microwave frequencies," *Phys. Rev. Letters*, vol. 12, pp. 325–327, March 23, 1964.

[4] R. W. Damon, and H. van de Vaart, "Microwave pulse echoes with variable time delay by parametric pumping of traveling spin waves," *Appl. Phys. Letters*, vol. 6, pp. 194–196, May 15, 1965.

Linear Tuning of a Microwave Cavity

The usual tuning devices used with microwave cavities have pronounced nonlinear (frequency vs. probe position) characteristics because of their operation in nonuniform fields. The arrangment[1] described here encloses a small tuning probe with a dielectric sleeve of such shape as to improve the uniformity of the field around the probe and consequently the linearity of tuning over a useful range of operation.

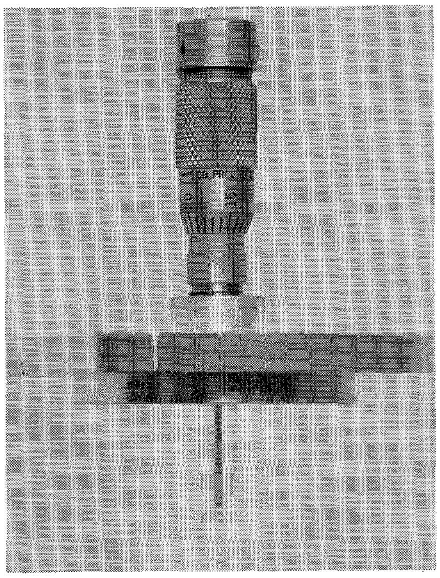

Fig. 1. Tuning probe enclosed in specially-shaped dielectric sleeve.

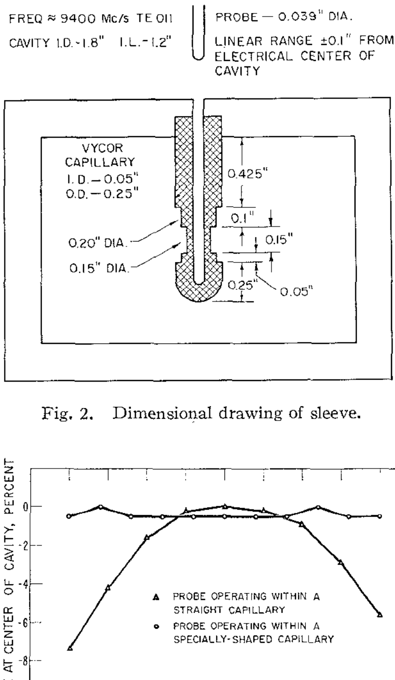

Fig. 2. Dimensional drawing of sleeve.

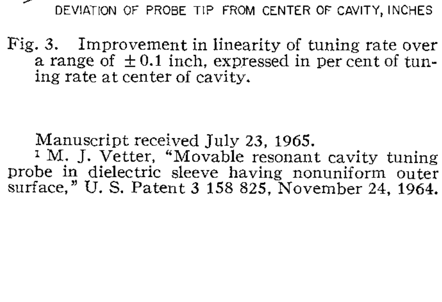

Fig. 3. Improvement in linearity of tuning rate over a range of ±0.1 inch, expressed in per cent of tuning rate at center of cavity.

General physical characteristics are shown in Figs. 1 and 2. The Vycor capillary has characteristics similar to fused quartz with a dielectric constant of approximately 3.8 and a very low dissipation factor.

Basically, the tuning probe is enclosed by more of the dielectric material in regions where the electric field would tend to be lower. This material concentrates the field in these regions and results in a uniform field over the desired range.

The choice of dimensions was arrived at empirically, and the effects are shown in Fig. 3.

A number of factors determine the optimum shape for the sleeve and effectiveness of the system. These include the dielectric constant of the sleeve, the diameter of the probe, the dimensions and configuration of the cavity, and the moninal field distribution in the region of the probe. The same concept could be used on cavities operating in other than the TE011 mode that was used here.

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Manuscript received July 23, 1965.

[1] M. J. Vetter, "Movable resonant cavity tuning probe in dielectric sleeve having nonuniform outer surface," U. S. Patent 3 158 825, November 24, 1964.

Experimental Results in Groove Guide

This correspondence is concerned with the following developments in low-loss groove guide:

1) development of a transducer [1] from rectangular H_{10} mode to groove guide H_{11} (low-loss) mode,
2) experimental determination of transducer performance,
3) experimental verification of the dispersion relation and the attenuation constant obtained from the approximate theory developed by Ruddy [2]–[4] and Griemsmann [5] at the Polytechnic Institute of Brooklyn (PIB).

The mode transducer configuration is shown in Fig. 1. The inset shows a side view. The design is based, in some degree, on experience gained in the development of a mode transducer for low-loss H-guide [6] at PIB.

The transition is accomplished in two distinct steps. The first step is a transformation from rectangular waveguide to a special groove guide in which the plate separation b' in the extra-groove region is smaller than normal design value. This dimension is chosen such that the H_{10} parallel plate mode will be below cutoff for the highest frequency

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