Experimental investigation of magnetostatic surface wave amplification in GaAs-yttrium iron garnet layered structure

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This paper describes the experimental results of the active interaction between drifting electron streams in n-GaAs and magnetostatic surface waves propagating on a relatively thin yttrium iron garnet (YIG) slab. A large relative gain of up to 17 dB is attained at a delay time of 0.15 μs by fine adjustment of this novel coupled system. This result corresponds to almost recovering the loading loss of the semiconductor in the whole delay time range observed. The effect of temperature on the amplifying characteristics is also studied by varying the repetition frequency in the pulse experiment.

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The magnetostatic surface wave (MSSW) amplification by drifting carrier streams in a semiconductor-yttrium iron garnet (YIG) layered system has been discussed theoretically by a number of investigators.[1–3] However the gain obtained in the other experiments[4–6] so far is very small, because the interaction between the MSSW in a thick slab of YIG (0.5–1 mm) and the carrier wave in Ge is weak. In order to get a large gain, it is necessary to use a high mobility semiconductor, for instance, GaAs at room temperature and a thin YIG slab with low loss, as pointed out already in the theoretical investigation.[2]

We describe here the amplifying characteristics of the MSSW obtained in the novel layered structure composed of a n-GaAs slab with a higher drift velocity of electrons and a relatively thin YIG slab (0.09 mm) having a slower MSSW phase velocity. We have varied the thickness of the spacer between YIG and GaAs in order to find optimum coupling conditions. In the coupled systems with adjusted parameters, a maximum relative gain of 17 dB is obtained at a delay time $\tau = 0.15\ \mu$s, and the loading loss of the semiconductor is almost recovered by the amplification in the range $\tau = 0.1 - 0.7\ \mu$s. The heat generation in semiconductor samples is one of the major problems in actual device development, so we investigated the effect of temperature on the amplifying phenomenon by changing the repetition frequency of drifting electric pulse with a constant pulse width. The small positive gain obtained in our experiments is the first such result, to our knowledge, concerning gain in the magnetostatic wave amplifier.

Our interaction system schematically shown in Fig. 1 is composed of a GaAs slab, a dielectric spacer, and a YIG slab. The dimension of the YIG slab is $8\times4\times0.09$ mm^3, the saturation magnetization $4\pi Ms = 1750$ G, and the ferromagnetic resonance line width $\Delta H = 0.5$ Oe. The semiconductor used here is a bulk crystal of n-GaAs having the following physical parameters: electron density $n_e = 8.1\times10^{15}$/cm^3 and electron mobility $\mu_e = 6.13\times10^3$ cm^2/V s at room temperature. Twelve GaAs specimens having different sizes (length 2–5 mm and width 0.5–2.0 mm) and the same thickness, about 80 μm, were fabricated. These were combined with the YIG slab. The resistance of these GaAs specimens ranged from about 40 to 240 Ω and their I-V characteristics revealed essentially straight lines in the applied voltage range $V = 0 - 700$ V. The prepared dielectrical spacers were of four thicknesses: 155, 115, 74, and 65 μm. The materials used were glass for the 155-μm spacer and Polyimide plastics for the others. The latter has a dielectric constant $\epsilon_s = 2.6$ and a loss $\tan\delta = 2\times10^{-3}$ in the vicinity of the operation frequency. The excitation and detection of the MSSW are done by attaching an 80-μm-diam gold wire to the YIG surface. In the configuration of Fig. 1, the direction of electron drift indicated by v_d corresponds to the positive interaction.

Our amplification experiments were carried out by the pulse method.[6] A microwave signal modulated by a pin diode was fed to the input coupler, and the MSSW output was

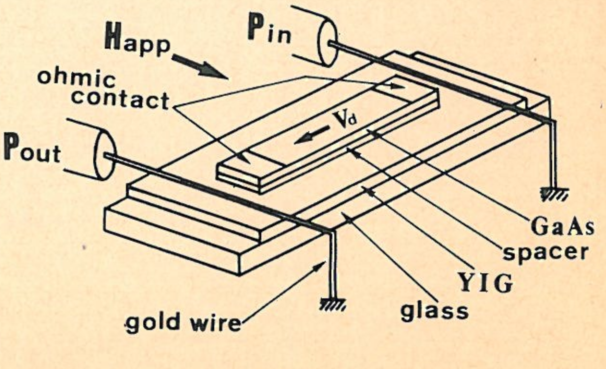

FIG. 1. A schematic configuration of the interaction system. The electron drift direction is the same as that of the phase velocity of MSSW. Only this direction gives the positive interaction (amplification), which is also indicated in the figure by v_d.

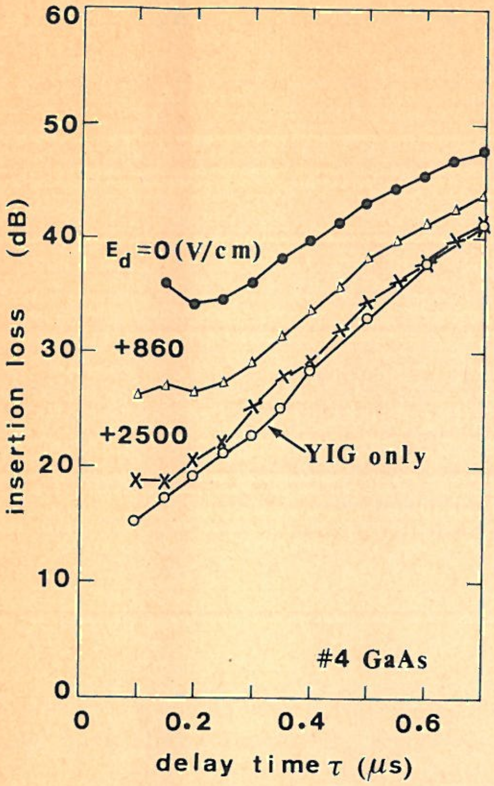

FIG. 2. Insertion loss as a function of the delay time of MSSW with the electron drift velocity, namely applied electric field, as a parameter; GaAs specimen is No. 4, $f = 4.2$ GHz, $P_{in} = 7$ dBm, $\tau_{pd} = 1.2$ μs, and $f_r = 200$ Hz. Spacer thickness $t_s = 65$ μm.

downconverted to intermediate frequency (IF) and detected where the electric fields synchronized with microwave pulses were applied to GaAs. The loss variations of MSSW associated with the interaction were recorded. In the experiments, the following conditions were employed: operation frequency $f = 3.6 - 4.3$ GHz, input power $P_{in} = 7$ dBm, pulse width of pin diode $\tau_{pm} = 0.1$ μs and pulse width of drift voltage $\tau_{pd} = 0.6$–1.4 μs. The repetition frequency f_r was properly selected in the range 10 to 500 Hz.

Figure 2 shows the variation of an insertion loss corresponding to the gain factor as a function of MSSW delay time, with the electric field strength E_d in GaAs as a parameter. The data were obtained when the spacer thickness was 64 μm and the semiconductor size was $5\times0.5\times0.08$ mm^3 (No. 4 specimen). These dimensions were carefully selected so as to increase the gain by combining the spacer and the GaAs slab with a relatively narrow width to decrease the semiconductor loading loss.

When the GaAs is loaded on the YIG slab, the loss level which appeared at $E_d = 0$, as shown in Fig. 2, increases from that with YIG alone. Then the increased losses are gradually recovered as E_d increases and the relative gain $G_r = 17$ dB is obtained at a delay time $\tau = 0.15$ μs for $E_d = 2.5$ kV/cm. But G_r decreases to about 7 dB as τ is increased to 0.7 μs. The loss of the amplified MSSW is thus finally restored to almost that of the equal YIG alone. Measured data of gain, as a function of E_d, agree qualitatively with theoretical result.[2]

Figure 3 shows the detected MSSW IF output oscillo scope traces together with the drifting pulses corresponding to the results of Fig. 2. Since the coupling loss is as low as about 10 dB, the drift leakages between couplers are almost entirely suppressed in these tracers. For both $\tau = 0.2$ and 0.4 μs, the amplitudes of the MSSW become larger as E_d increases, but G_r is not linear in E_d. It usually shows a tendency to become saturated with E_d. According to the theory,[2] G_r is proportional to the drift velocity $v_d(\mu_e E_d)$ of electron carrier streams. Since v_d is not linear in E_d for high E_d, the gain profile has a tendency to saturate in the high E_d region. Increasing the input bias power contributes to broadening out ΔH through the temperature increase and facilitates the saturation of gain.

Finally, we describe briefly the effect of temperature in this type of interaction. The repetition frequency was, so far, usually selected as several tens of hertz.[5,6] We have investigated this effect by examining the experiments with various

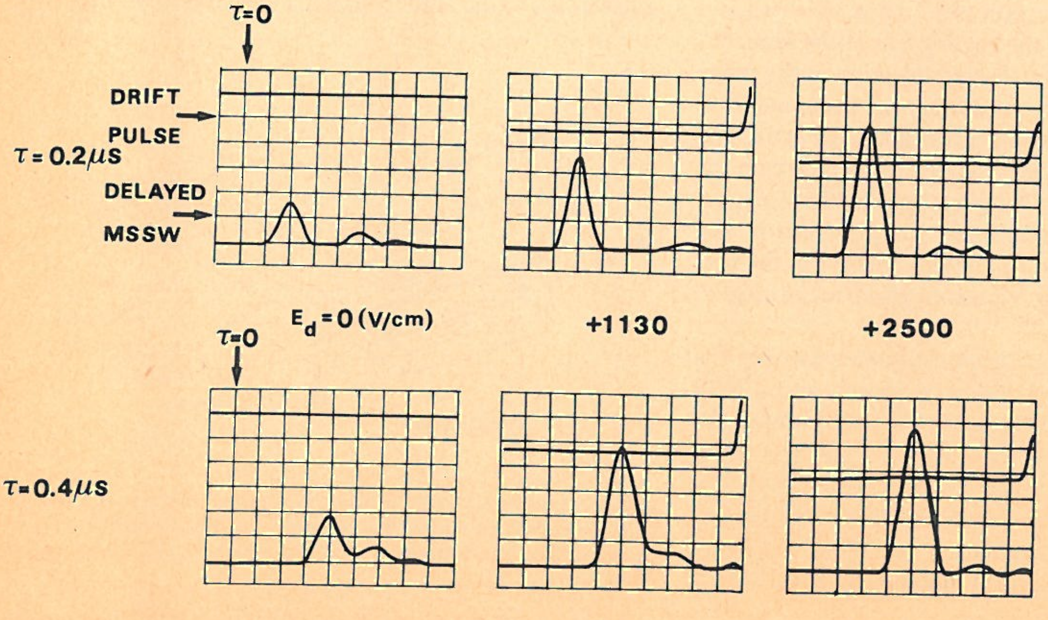

FIG. 3. Detected MSSW IF output waveforms together with monitored drifting voltage pulse applied to No. 4 GaAs slab. Vertical scale: 200 mV/div for $\tau = 0.2$ μs, and 100 mV/div for $\tau = 0.4$ μs (applicable to MSSW trace only). Horizontal scale: 0.1 μs/div.

repetition frequencies under constant strength and pulse duration of drifting voltage. The saturation of G_r with E_d took place more rapidly as f_r increased, in other words, the value of E_d giving maximum G_r was found to decrease gradually. For example, in the coupling system utilizing No. 10 GaAs specimen ($4\times1\times0.06$ mm^3), $E_d(G_{r,\max})$ has fallen from 1.75 kV/cm at $f_r = 10$ Hz to 1.0 kV/cm at $f_r = 400$ Hz for $\tau = 0.15$ μs microwave signal, where $G_{r,\max} = 7.5$ dB was almost constant. This property indicates the presence of a maximum power loss in the GaAs sample which is of the thermal threshold type. If this is true, it is reasonable to assume that G_r saturates at lower E_d as f_r is increased, because the increase in f_r is equal to the increase of power injected per unit time.

As mentioned above, we have observed a strong and convincing interaction between a MSSW ferrite-air mode and electron drifting streams in the GaAs-YIG novel hybrid system. Although important information for designing this type of device was obtained here anew, the insertion loss level of the system attained by the amplification is still large compared with the usual microwave amplifier. In order to decrease the loss of the system further by a stronger interaction, we will, in the next step, adopt low-loss liquid-phase epitaxial YIG films with microstrip transducers and high-mobility epitaxial GaAs specimens.

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