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Application of Nonlinear Magnetostatic Waves in the Construction of Thin-Film Solid State Devices

A.D. BOARDMAN*, Yu.V. GULYAEV**, S.A. NIKITOV**

Dept. of Physics, Salford University, Salford
M5 4WT, U.K.
IRE Academy of Sciences, Marx Av, 18, 103 907,
Moscow, USSR.

The theory of the propagation of nonlinear magnetostatic surface waves (MSSW) in thin ferromagnetic films is developed. New results considering the formation of MSSW pulse envelope solitons, the propagation of nonlinear MSSW in periodic structures that produces multistable characteristics and the diffraction of wave-guided optical frequency electromagnetic waves by nonlinear MSSW, are presented. A discussion is also given of the potential implied by these effects for the production of new nonlinear microwave and magneto-optic devices in solid state electronics.

It is now well-known that a new class of solid state devices can be constructed[1,2], using magnetostatic waves (MSW) as their basis. These waves can propagate, for example, in ferromagnetic materials in the high frequency part of the microwave spectrum. The technology now exists for the preparation of high quality thin-films of yttrium-iron-garnet (YIG), a fact that permits the construction of these devices in micro-miniature form. Such YIG films also have a very narrow ferromagnetic resonance linewidth (0.1 Oe). This is the main parameter that determines the damping of the MSW so that its propagation distance is quite large and is comparable with any desired crystal size. There are many proposed devices[1,2], based upon MSW but this paper will consider the possible new applications, based upon nonlinear MSW, having first developed the general theory of nonlinear MSW propagation in ferromagnetic thin films.

There are three types of MSW that can propagate in thin ferromagnetic films, namely forward volume, backward volume and surface magnetostatic waves. In this paper attention will be focussed upon surface magnetostatic surface waves (MSSW) for use in solid-state devices, because their frequency is higher than the frequency of volume waves, and because the value of external magnetic field defines the region of frequency space in which they exist. In the first part we derive the CW nonlinear dispersion equation of MSSW that may propagate in any direction of the plane containing the ferromagnetic film. It is shown that the sign of the nonlinear coefficient in this MSW dispersion equation can change its value as the angle between propagation direction and the applied magnetic field is varied. It is also shown that the second derivative of the group velocity of the MSSW (group velocity dispersion) always has a permanent negative sign. In the angle regime where the nonlinear coefficient is positive solitons can exist. The nonlinear Schrödinger equation that describes the propagation of envelope MSSW solitons is derived and numerical estimates are given that show that threshold energy needed to generate first-order MSSW solitons is of the order of a few mW and that the soliton length, in which a balance between nonlinearity and dispersion is achieved, is approximately 1 cm. for a YIG film of thickness 10 μ and an applied magnetic field of 1 kOe. The propagation of nonlinear MSSW in a ferromagnetic film with one periodically corrugated surface will also be discussed. This periodic structure supports magnetostatic waves that exhibit bistable properties above a certain threshold power. This is because the nonlinearity creates changes in the propagation characteristics of the MSSW that are reflected and transmitted through the periodic structure. These changes can create multistable states of the propagating waves and the dependence of the output power on the input power of the wave for this structure displays hysteresis. As an example a nonlinear Fabry-Perot resonator is examined in detail. The value of the power threshold for the onset of multistability depends upon the value of the small parameter characterising the periodic structure. It can be chosen to be sufficiently small that the value of the power threshold will be less than needed for the creation of MSSW solitons. It is estimated that this effect can occur for very small values of the MSSW power.

The final part of this paper concerns the problem of diffraction of guided electromagnetic waves by the nonlinear MSSW. There is, in this case, a magneto-optic interaction in which the dielectric permeability tensor of the ferromagnet has off-diagonal terms that depend upon the power of magnetostatic wave. It is shown that strong coupling between the propagating and diffracted modes exists both through magneto-optical effects of the first kind (Faraday effect) and the second kind (Cotton-Mouton effects). The coupling coefficient between TE and TM modes propagating in the ferromagnetic film waveguide is derived and the additional diffraction introduced by the nonlinearity of the MSSW is presented. For YIG-films doped by ions of Bi (which permits the Faraday effect), and for and MSSW power level of a few microwatts, the magnitude of the mode conversion may reach 50%.

A discussion is presented concerning the potential these effects have for the production of new nonlinear microwave and magneto-optic devices. They can obviously be used for constructing convolvers, nonlinear magneto-optic modulators, deflectors and tunable filters. In comparison with linear devices, however, they have a big advantage because their properties can be controlled by changing the power level of the wave.

1) A.D. Fisher, J.M.M. Lee, E.S. Gaynor and A.B. Tveten. Proc., 1982 IEEE Ultrasonics Symp., 541 (1982).

2) A.M. Prokhorov, G.A. Smolenskii and A. Ageev, Sov. Phys. Usp. 27,339(1984).