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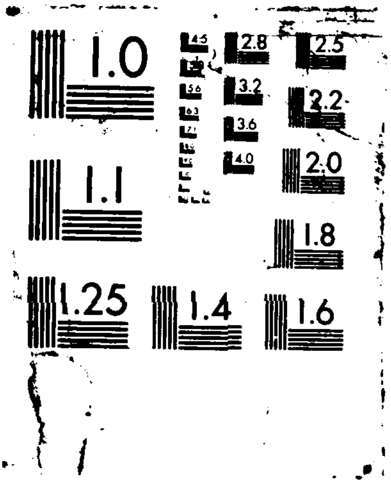
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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This project involved a general theoretical study of magnetic properties of layered systems. Three major areas were:

(1) Phase transitions in magnetic superlattices
(2) The excitations in thin films and layered structures and the connection to optical properties
(3) Nonlinear optical properties of thin films and layered structures

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MAGNETIC SUPERLATTICES

FINAL REPORT

by

R. E. CAMLEY

JANUARY 13, 1988

U. S. ARMY RESEARCH OFFICE

CONTRACT # DAAG29-84-K-0201

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STATEMENT OF THE PROBLEMS STUDIED

This project involved a general theoretical study of magnetic properties of layered systems. Three major areas can be identified:

1) Phase transitions in magnetic superlattices
2) The excitations in thin films and layered structures and the connection to optical properties
3) Nonlinear optical properties of thin films and layered structures

Below we discuss each of the three areas in more detail.

Phase transitions in magnetic superlattices

The basic question here is - how does temperature or an applied magnetic field change the ground state properties of a magnetic superlattice? The particular ground state of a magnetic superlattice determines the fundamental macroscopic properties of the superlattice, including the magnetization and the static and dynamic susceptibility. Since these macroscopic properties are of great practical importance, a second important question is - can the ground state be easily adjusted by changing the layering pattern of the superlattice so that the macroscopic properties can be tailored to desired applications?

Excitations in thin films and layered structures and the connection to the optical properties of these materials

The fundamental spin wave excitations in a magnetic system are a primary influence on the optical response of the material. For metallic ferromagnets the frequency range of interest is that of 10-20 GHz while for antiferromagnets, the frequencies lie in the infrared. Magnetic systems thus offer the possibility of performing optical processing over a large frequency range. In addition, magnetic systems have unique features which make them particularly interesting for signal processing. First, since the frequency of spin waves is generally dependent on an applied field, the optical response may be tuned by the use of an external field. Second, surface spin waves are frequently nonreciprocal and can be effectively used in isolators and gyrators. Thus in this portion of the work, we calculated the spin wave excitations for a variety of materials (ferromagnets and antiferromagnets) and in a variety of layered structures (thin films and superlattices). From these calculations, the optical behavior of the materials was found.

Nonlinear Optical Properties of Thin Films and Layered Structures

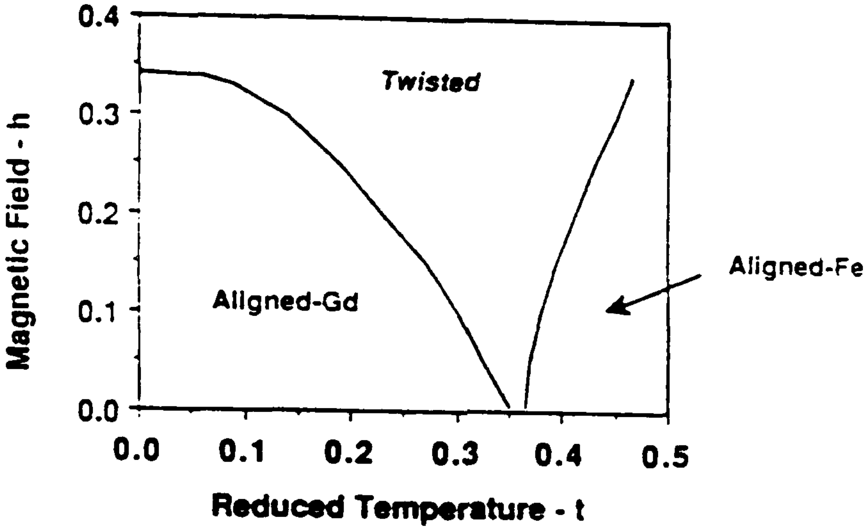
Optically nonlinear materials (where the dielectric constants or magnetic permitivity includes a term which is dependent on the local intensity) show remarkable behavior which can be used in signal processing. For example, bistability, a switching from a transmisivity of zero to a transmisivity of one as the power is increased is a common feature in nonlinear systems. The major goal in this portion of the research was to see if the confined geometries of a thin film or a superlattice can be used to fundamentally influence the nonlinear optical properties of materials. Since magnetic materials can be highly nonlinear, we considered as a specific application a nonlinear antiferromagnet. Since antiferromagnets have resonance frequencies which lie in the infrared, these materials might be used as nonlinear circuit elements in optical systems designed to operate in the infrared.

SUMMARY OF MOST IMPORTANT RESULTS

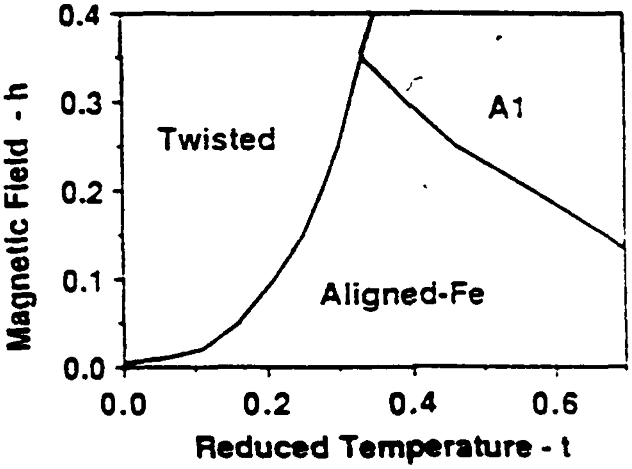
Phase Transitions in Magnetic Superlattices [publications 2,4,6,9,16,19]

We found that the most interesting systems contained spins which were both ferromagnetically and antiferromagnetically coupled. We first explored the magnetic ground state at zero temperature as a function of an applied field for a superlattice composed of alternating ferromagnetic and antiferromagnetic films. The competing interactions led to a variety of possible phases. These include an aligned state where the Zeeman field is so strong that all spins align parallel to the applied field, a superlattice spin flop state where the transverse moments in alternating ferromagnetic films alternate in sign, and a twisted state where the spins in each layer make a different angle with the field. The phase transitions (due to the applied field) were all of second order. Furthermore, the field at which the transitions occur is a sensitive function of the number of layers in both the ferromagnet and antiferromagnet. Thus changing the layering pattern slightly leads to significant changes in magnetic ground states, and this in turn leads to large changes in the macroscopic properties of the superlattice.

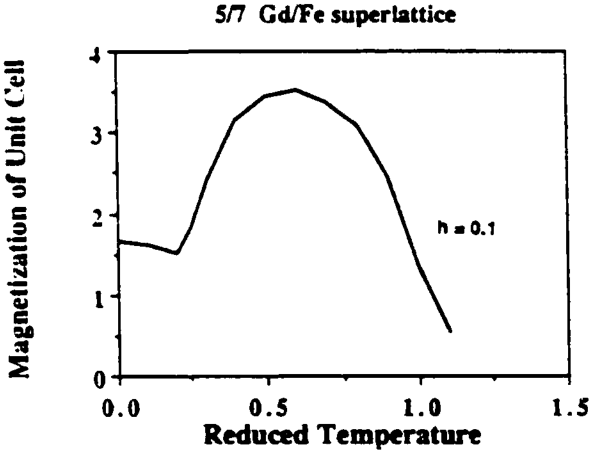
As a second major example, we studied the magnetic field - temperature phase diagram for a model system composed of alternating films of two ferromagnets, Fe and Gd. Although the materials, by themselves, are ferromagnets, they couple antiferromagnetically at the interfaces. Again a variety of phases were possible, the most notable being the aligned phases where Fe and Gd were strictly antiparallel, and the twisted phase where the spins in different layers made different angles with the applied field. We found that the ground state properties were strongly dependent on the layering pattern. In a system where the unit cell had 4 layers of Gd spins and 4 layers of Fe spins the H-T phase diagram looked like

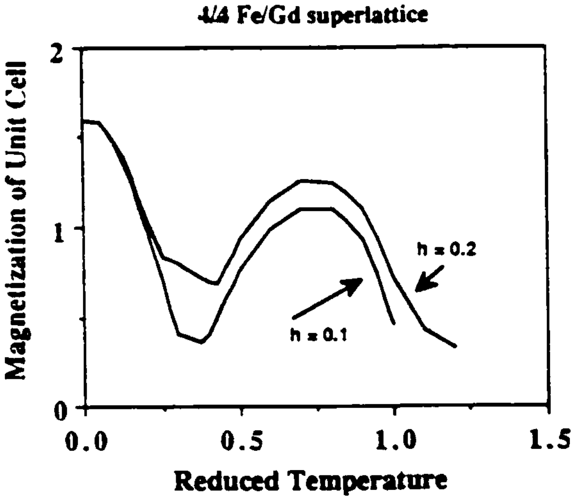


In a system with a unit cell of 7 layers of Fe spins and 5 layers of Gd spins the phase diagram was given by the figure below.



The point of this is that small variations in the construction of our superlattice leads to large variations the ground state. This leads to fundamentally different macroscopic properties. For example, one can now calculate the magnetization as a function of temperature. For the 4/4 Fe/Gd and the 5/7 Gd/Fe superlattices this leads to the very unusual curves shown below!





Clearly, one can tailor the magnetic properties of materials by changing a layering pattern in the superlattice.

Excitations in thin films and layered structures and the connection to the optical properties of these materials [publications 1,2,3,4,5,6,7,8,9,12,13,18,20]

We studied the spin wave modes of a thin antiferromagnetic film both in the long wavelength limit and a medium wavelength limit. The medium wavelength limit is particularly interesting because the frequency of the modes then depends on the microscopic surfaces of the film. In particular, in the absence of an applied field an antiferromagnetic film with (100) surfaces can have nonreciprocal surface wave propagation while one with (110) surfaces has reciprocal surface wave propagation. Also, in certain geometries ((100) surfaces and the same sublattice appears on both surfaces) the dipole-exchange modes may be localized to one surface of the antiferromagnet without the presence of an applied field.

In a particularly exciting development, we compared theory and experiment for the reflection of 264 GHz radiation from the surface of an antiferromagnet. It was found that the reflection was nonreciprocal, ie. the reflection coefficient depended on whether the wavevector for the surface wave was positive or negative. The difference in the reflection coefficient for an incident wave

wave traveling in the +x direction and one travelling in the -x direction was found to be as high as 50%. Such nonreciprocal behavior is used in ferrite devices which operate at lower frequencies. The possibility of nonreciprocal devices operating in the 200 GHz range is very exciting.

The spin wave spectrum for magnetic superlattices was also calculated. While these are fundamentally interesting by themselves, we also calculated the infrared absorption spectrum of these superlattices due to the spin waves. It was found that the absorption spectrum could be very different in the different phases of the superlattice. Thus application of a magnetic field (which can change the ground state of a superlattice) can significantly change the IR absorption spectrum. Again this leads to the possibility of tunable filters in the infrared. In addition to spin systems, we also studied plasmons and electrons in superlattices. Although we did not pursue this, these excitations also will affect the optical properties of the materials.

Nonlinear Optical Properties of Thin Films and Layered Structures

[publications 14,15,16]

The reflectivity and transmisivity of both bilayer and multilayer structures case calculated. Some fascinating results emerged. The bilayer shows the usual nonlinear bistability, but with a nonreciprocal character, i.e. the threshold for the onset of bistability with the light incident from one side of the bilayer may differ substantially from that with the light incident from the other side. Superlattices also showed interesting results. At low power levels, superlattices show "stop gaps" where propagation is not normally allowed. In the nonlinear superlattice, the system may switch from low transmisivity in these stop gaps to high transmisivity at rather low incident power levels. This offers considerable promise in creating devices for optical computing.

In addition to the superlattice work, we considered the nonlinearity in a thin antiferromagnetic film. The theoretical results show that antiferromagnetic films can exhibit bistability in the far infra-red for power levels that are accessible in the laboratory.

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    B. L. Johnson and R. E. Camley, Physical Review B - submitted

ALL PARTICIPATING SCIENTIFIC PERSONNEL AND ADVANCED DEGREES

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B. L. Johnson - graduate student - earned a Masters degree

At University of California, Irvine

D. L. Mills - Principal Investigator

L. L. Hinchey - graduate student - earned a Ph.D.

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