Properties of high-frequency granular magnetic materials

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Soft magnetic materials, i.e. materials with a high permeability, are used in various devices for power, RF, and microwave applications. It is particularly important to engineer high-mu and low-loss magnetic materials. Permeability of a material is an extrinsic property, i.e. it is determined not only by intrinsic bulk parameters but also by the material composition. Granular magnetic materials are comprised of randomly hard magnetic grains that are exchanged coupled to result in soft properties. These materials combine the ability to have a high permeability with low conductivity. Generally, these materials are characterized by non-reciprocal dispersive tensors and identifying their properties can be a complicated task.

In this work, an analytical model and computational framework are presented for the study of granular soft magnetic materials. These models are applied to the study of exchange coupled random ferromagnetic grains with grain size on the order of a few nanometers. The numerical model involves solving the Landau-Lifshitz-Gilbert equation via a high-performance simulator FastMag, which allows calculating the hysteresis loop and extracting the permeability tensor. A time and frequency domain approaches can be followed. In the time domain approach the time domain LLG equation is solved and the permeability tensor is obtained by Fourier transform. This approach is applicable for linear and non-linear responses but it can be relatively slow. In the frequency domain case, linearized frequency domain LLG equation is solved. This approach can be faster but it is not applicable to non-linear cases. The analytical model provides a simplified approach to finding the magnetic properties and it is based on statistical averages over the grain properties in a certain rigorously defined exchange zone.

The model clearly shows that soft magnetic properties are obtained mostly due to the exchange coupling and random orientation of the grains. Long-range magnetic field coupling also plays a role in shaping the magnetic properties. We study effects of material properties, including grain size, inter-grain spacing, saturation magnetization, and crystalline anisotropy on the magnetic properties. Furthermore, the tensor alignment can be controlled by magnetic annealing. Annealing can be done non-uniformly to result in a predefined distribution of the tensor, thus providing flexibility in designing magnetic properties of granular films.

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