Quasi-optical Measurements of Magnetic Materials at Frequencies up to 630 GHz

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***Abstract*—this paper investigates complex refractive index and wave-impedance of commercial permanent-magnet hexaferrites, which are suitable for use in quasi-optical nonreciprocal devices at millimeter and submillimeter wave frequencies. The measurements are realized by using broadband quasi-optical bench and vector network analyzer in the frequency range 75-630 GHz.**

I. INTRODUCTION AND BACKGROUND

HIGH-performance quasi-optical non-reciprocal devices (isolators, circulators) are required for use in many current and future measurement systems operating at millimetre(mm)-wave/submillimetre-wave frequencies. In these devices, the magnetic material that provides the non-reciprocal function is in the form of a thin-plane plate, uniformly magnetised perpendicularly to its surfaces, and sandwiched between dielectric matching plates. A candidate magnetic material must have both the necessary gyrotropic magneto-optical properties and low loss RF properties at mm-wave/submillimeter-wave frequencies [1-2]. In this paper, we use a vector-network-analyser (VNA) to make measurements on a quasi-optical circuit. Using the full range of functions provided by the VNA, the linear-polarisation transmittances, co- and cross-polar, of the plate are determined in amplitude and phase. From these data the circular-polarisation transmittances, of both senses are computed and these are analysed to determine the magneto-optical constants of the material (*i.*e. the complex refractive index and the complex wave-impedance, for both senses of circular polarisation) over the range of mm-wave frequency.

II. W-BAND MEASUREMENT OF FERRITES FROM THE SAME BATCH

The twenty same-thickness (2.02mm) FB6H ferrite samples from the *same* batch (kindly supplied by TDK) were initially measured at Queen Mary's Antenna Measurement Lab (AML). The twenty samples are divided into four groups and their amplitudes of positive-circular transmittance in a group are co-plotted in one subsection of Fig.1. The results in Fig.1 indicate clear differences in the refractive indices of the plates, even though they come from the *same* batch with the *same* thickness. For this reason, it is necessary to measure every each potential candidate sample, to accurately determine to good precision its magneto-optical constants, which are the basis for designing high-performance non-reciprocal device.

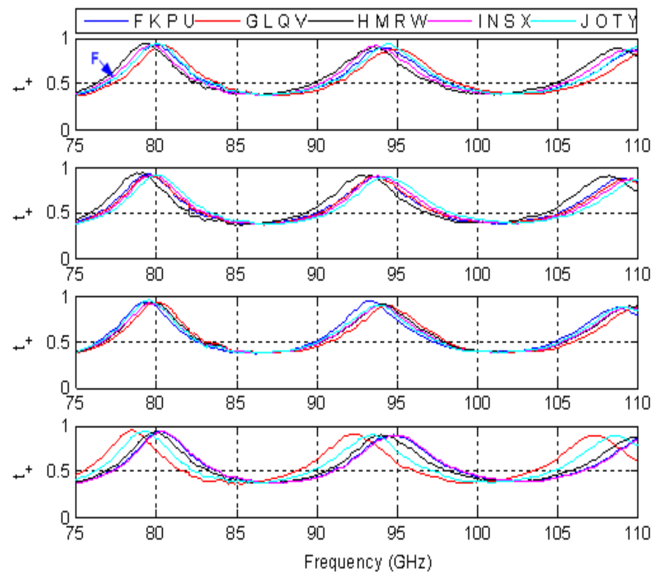

Fig.1 *The t_+ transmittance of a batch of twenty ferrite samples (the samples are randomly labelled by letters from F to Y) having the same thickness; letter-sequences are read top-to-bottom. For example, the amplitudes of the sample F, K, P and U are all plotted by blue curves, but they are displayed in different subplot sections.*

III. MEASUREMENT RESULTS AT HIGHER FREQUENCY (110-630 GHZ) BANDS

Measurements were performed at ABmm Ltd in Paris using its VNA over the frequency range 110 - 630 GHz. The 'ultra' Gaussian corrugated horns designed and supplied from Thomas Keating Ltd (TK) [3] are firstly used to make the measurements. The horns are able to significantly reduce the modal resonance, whilst producing far field beam patterns with very low side-lobes and phase centers in the horn-aperture.

Before starting measurements on unknown and complex ferrite materials, a standard dielectric of Si in plate-form, whose polarization response is well known, is measured to check for systematic errors in our measurement system and experimental method. The calculated constants of the silicon are plotted in Fig.2. Refractive indices are in the range of 3.424±0.020 over the frequency band 110 - 600 GHz and they agree with previously published data [4-5], and the estimated normalized wave-impedance ratio is, as expected, approximately equal to the reciprocal of the refractive index. The results for the silicon indicate that the measurement system and methods and the procedures for determining refractive indices and wave-impedances are accurate with the required precision and free from significant systematic errors over the frequency domain (110 - 600 GHz).

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Uncertainties of determined magneto-optical constants are mainly dominated by random errors due to frequency and amplitude drift arising from source and electronic instabilities in the VNA of ABmm and the limited dynamic ranges. A statistical experiment is used to simply estimate a typical ±0.36% frequency- and ±0.47% amplitude-drift over a given time interval. According to these statistical deviations, the uncertainties of estimates in refractive index are less than ±0.4% and uncertainties in estimates of normalized wave impedance are less than ±1%.

During the measurements of the twenty FB6H samples in the AML of QMUL, sample V was found to be very low loss. It had ~ -0.05 dB/mm insertion loss at 94.60 GHz. It therefore suggested itself as a high quality candidate for use in high-performance quasi-optical non-reciprocal devices. The calculated positive/negative circularly-polarised refractive indices are plotted in Fig.3. The magneto-optical constants are determined only up to 400 GHz, as the sample is too lossy above 400 GHz and the algorithm for determining magneto-optical constants is only suitable for low loss materials. The positive circularly-polarised refractive index is slightly dispersive at lower frequencies due to the near-lying magnetic resonance, however this dispersion diminishes upon increasing away to higher frequencies. The insertion loss of sample V at 400 GHz is ~ -1 dB/mm.

IV. CONCLUSIONS

This paper reports for the first time physical measurement of ferrite transmittance over a spectral domain from 110 GHz to 630 GHz. Objective and direct estimation of magneto-optical constants up to 400 GHz (and up to 600 GHz for silicon optical constants), are also presented. The uncertainty of estimated values of refractive index is less than ±0.4% and the uncertainty of estimated normalized wave impedance is less than ±1%. FB6H sample V and others from the same batch prove themselves to be very good candidates for the design of high performance quasi-optical non-reciprocal devices in the mm-wave domain (below 400 GHz).

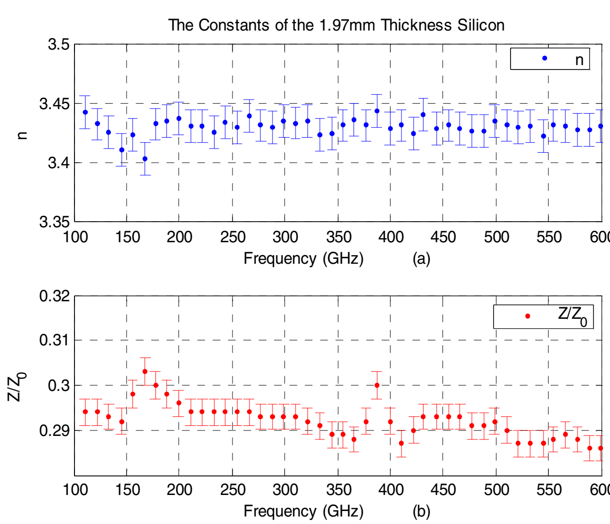

Fig.2: 1.97 mm thick silicon's optical constants; a) refractive index (blue dot curve with ±0.4% error bar); b) normalized wave-impedance (red dot curve with ±1% error bar).

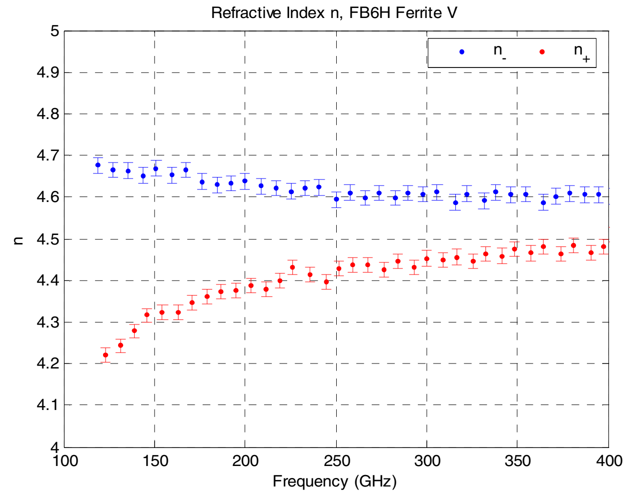

Fig.3: Positive (red points with ±0.4% error bar) / negative (blue points with ±0.4% error bar) circularly-polarised refractive indices of 2.02 mm thick FB6H hexaferrite sample V.

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