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Bloch Vector Analysis in Nonlinear, Finite, Dissipative Systems: An Experimental Study

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Abstract: We have investigated and experimentally demonstrated the applicability of the Bloch vector for one-dimensional, nonlinear, finite, dissipative systems. The case studied is the second harmonic generation from metallo-dielectric Ag/Ta₂O₅ thin film multilayer filters.

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1. Introduction

The Bloch theorem and the Bloch vector are central in many fields of physics ranging from solid state physics to optics and photonics [1]. The Bloch vector for a 1-D, periodic structure comes directly from the Bloch theorem and can be written as [1]: $K_\beta(k_x, \omega) = (1/\Lambda) \cos^{-1}[(1/2)(m_{11} + m_{22})]$, where \cos^{-1} is the inverse cosine (arccosine) function, k_x is the transverse wave-vector along the x-axis, i.e. in the direction perpendicular to the periodicity (z-axis), Λ is the length of the elementary cell of the structure and m_{ij} are the elements of the transfer matrix of the elementary cell. The question that arises is whether or not the Bloch vector continues to give useful information when one deals with nonlinear, dissipative structures of only few periods in length. In order to shed some light on the question we study second harmonic generation (SHG) process from three metallo-dielectric (MD) structures and examine the possibility of interpreting the results in the frame-work of a Bloch vector analysis.

2. Results and Discussion

The three samples fabricated by magnetron sputtering (sample (a), sample (b) and sample (c)) are made of N=5 periods of alternating layers of Ag and Ta₂O₅. The elementary cells are respectively: (a) [Ag(~21nm)/Ta₂O₅(~122nm)], (b) [Ag(~18nm)/Ta₂O₅(~152nm)], (c) [Ag(~18nm)/Ta₂O₅(~169nm)]. The fundamental frequency (FF) beam was provided by the output of a femtosecond Ti:Sapphire laser ($\lambda=800$ nm, 1 kHz repetition rate, 150 fs pulse width) with peak power of ~6GW/cm². Under TM polarization, the Helmholtz equation for the H-field at the SH ($\lambda=400$ nm) can be written as follows (see Ref. [2] for more details):

$$\frac{d^2 H_{y,2\omega}}{dz^2} + \left[\left(\frac{2\omega}{c} n_2(z) \right)^2 - (2k_{x,\omega}^{(in)})^2 \right] H_{y,2\omega} = 4\omega k_{x,\omega}^{(in)} \left[\epsilon_0 d_s^{(2)} \sum_k \delta(z - z_k) E_{z,\omega}^2 + \frac{2i\omega}{c^2} \gamma(z) E_{x,\omega} H_{y,\omega} \right]. \quad (1)$$

Eq.1 is valid layer by layer for TM→TM SH emission. The right-hand term contains the surface nonlinearity of the metal and the effect of the Lorentz force exerted on the free electrons of the metal [2]. In Fig.1 we show the experimental results and the comparison with the theory.

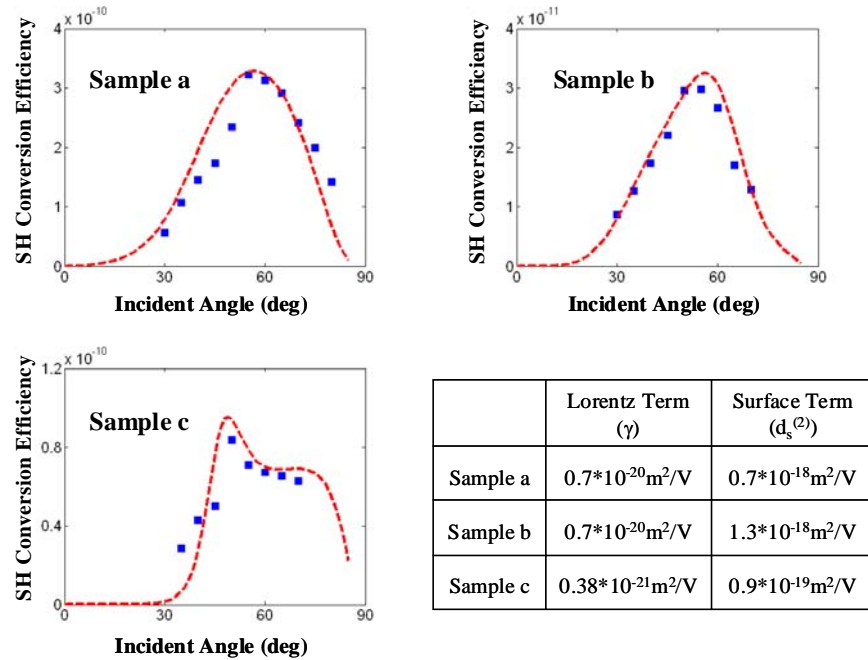


Figure 1 Reflected SH conversion efficiency vs. incident angle for TM→TM emission, theory (dashed line) and experiment (squares) for each sample. The incident intensity is $\sim 6 \text{ GW}/\text{cm}^2$. Table: Estimated values of the quadratic nonlinearities.

Note that while sample (a) and sample (b) have approximately the same values of the nonlinear coefficients, sample (a) results to have the strongest SH emission. Indeed it is the only sample that achieves a near phase matching condition with the first reciprocal lattice vector G_1 (this case is underlined in bold characters in the Table below).

	$\text{Re}K_{\beta, \text{FF}} (\mu\text{m}^{-1})$	$\text{Re}K_{\beta, \text{SH}} (\mu\text{m}^{-1})$	$G_1 (\mu\text{m}^{-1})$	$\text{Re}K_{\beta, \text{SH}} - 2 \text{Re}K_{\beta, \text{FF}} (\mu\text{m}^{-1})$	$\text{Re}K_{\beta, \text{SH}} + 2 \text{Re}K_{\beta, \text{FF}} (\mu\text{m}^{-1})$
Sample a	8.1	26.7	<u>43.6</u>	10.5	<u>42.9</u>
Sample b	11.7	29.5	36.7	6.1	52.9
Sample c	13.1	30.6	33.8	4.4	57.4

In the Table $\text{Re}K_{\beta, \text{FF/SH}}$ stands for the real part of the Bloch vector calculated from the expression given in the Introduction for the FF/SH fields respectively.

3. Conclusions

In conclusion, we have given experimental evidences that the Bloch vector continues to play a key role even in nonlinear phenomena involving finite, dissipative systems, such as SH generation in MD structures. Nowadays when metal based periodic nanostructures are of central importance in the field of nano-photonics, our results clearly suggest that the Bloch vector still remains fundamental.

4. References

- [1] P. Yeh, “*Optical Waves in Layered Media*”, Wiley, New York (1988)
- [2] G. D’Aguanno et al., Phys. Rev A **81**, 013834 (2010) and references therein