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Novel approach for designing a thin and broadband microwave absorber in Ku band based on substituted M-hexaferrites

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ABSTRACT

The design of novel microwave absorbers in the Ku band is still challenging. The aim of this work is to report the design of a new Ku absorber based on the combination of three M-hexaferrites with the formula of $BaX_{0.3}Y_{0.3}Cr_{0.3}Fe_{11.1}O_{19}$ ($XY=Co^{2+}Zr^{4+}$, $Zn^{2+}Ti^{4+}$, $Mn^{2+}Ce^{4+}$), 15 wt% of each in epoxy matrix. The results indicate the formation of a broadband absorber with a reflection loss (RL) lower than −10 dB over the whole bandwidth 13.75–18 GHz. It has three matching frequencies (14.2, 15.3 and 16.8 GHz) with RL (−29.2, −21.5 and −24.7 dB, respectively) at a matching thickness of only 2.5 mm. This is to be compared with the RL of the absorbers based on 45 wt% of each ferrite alone in epoxy matrix are (−15, −28.8 and −20 dB, respectively) at matching frequency of (14.15, 13.55 and 16.5 GHz) and a matching thickness of 4 mm. This favorable performance resulting from combining the three ferrites within the absorber may be attributed to the enhanced exchange coupling interactions between the three powders of distinct magnetic characteristics.

1. Introduction

The fast growth of telecommunication systems operating at high frequencies (MHz and GHz) increased the level of electromagnetic pollution that has harmful effects on human beings. Furthermore, this increase in the use of microwave radiation in modern telecommunication and data processing devices has given rise to electromagnetic wave interference (EMI), which is usually associated with poor performance of radar and microwave communication appliances. The lifetime and performance of communication and electronic devices can be increased by efficient EMI shielding. In this respect, the design of electromagnetic wave absorbing materials is an issue of great interest and has solicited intensive research over the last recent years [1,2].

It is well-known that ferrite materials are well suited for many EMI shielding applications. They can effectively reduce the reflection of electromagnetic signals and have low production cost [3]. Among ferrite materials, M-type hexaferrites are promising microwave absorbers since they have significant values of permeability. They absorb the microwave energy by lossy interactions of the wave magnetic field with their individual magnetization [4].

Numerous research papers have investigated the use of M-hexaferrite materials as microwave absorbers in the X band [4,5]. However, only few papers have explored their as an effective microwave absorbers in the Ku band [6,7]. This band usually extends from 12–18 GHz in the electromagnetic spectrum and is used primarily for satellite communications, particularly for editing and broadcasting satellite television.

On the other hand, it is well established that microwave characteristics of M-type hexaferrite depend critically on the synthesis method, temperature, type of substituted cations and their occupation site within Fe^{3+} sublattices. Many studies have been performed to modify the magnetic properties of barium hexaferrite by substitution of Fe^{3+} ions with various ions such as Cr–Zn [8], Co [9], Ce–Co [10], Co–Ti [11], La–Co [12], La–Ce–Zn [13], Zr–Cu [14] etc. However, the design of novel microwave absorbers with broad bandwidth, high reflection loss and thin thickness is still challenging.

The aim of this work is to report the design of a new broadband Ku band absorber based on three M-hexaferrites with the formula of $BaX_{0.3}Y_{0.3}Cr_{0.3}Fe_{11.1}O_{19}$ ($XY=Co^{2+}Zr^{4+}$, $Zn^{2+}Ti^{4+}$, $Mn^{2+}Ce^{4+}$). X-rays diffractometry, scanning electron microscopy and vibrating sample magnetometry are used to investigate the crystalline phase, morphology and magnetic properties of the synthesized ferrites, respectively. The measurements of the reflection losses (RL) in the Ku band of the composites are performed using a vector network analyzer. These ferrites have not been tested before as microwave absorbers in the Ku band. The combination of these

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three ferrites within the absorber matrix is also investigated. The present study constitutes, to the best of our knowledge, a novel approach to tailor the design of Ku absorber in order to meet the requirements of its designated application.

2. Materials and test methods

In this study, three types of doped M-type barium hexaferrite with the formula of $BaX_{0.3}Y_{0.3}Cr_{0.3}Fe_{11.1}O_{19}$ ($XY=Co^{2+}Zr^{4+}$, $Zn^{2+}Ti^{4+}$, $Mn^{2+}Ce^{4+}$) were synthesized via mechanochemical method. Raw materials of AR grades of $BaCO_3$, Fe_2O_3, CoO, ZnO, MnO, Cr_2O_3, ZrO_2, TiO_2 and CeO_2 were used. Planetary ball mill (Retsch PM100, 10 steel balls and average diameter of 15 mm, speed of 300 rpm) was used for milling the raw materials. Stoichiometric amounts of powder were mixed and ground with ball to powder weight ratio of 30:1 for 20 h in air atmosphere and then were calcined at the temperature of 1000 °C for 5 h with heating rate of 5 °C/min. In order to decreasing the particle sizes, the obtained powders were ground again for 1 h. Phase and morphology of the doped ferrites were respectively studied by X-ray diffraction analysis (XMD 300) and scanning electron microscopy (FE-SEM, MIRA3 TESCAN and SEM VEGA/TESCAN). Magnetic parameters of the samples were measured by vibrating sample magnetometer (VSM) at room temperature. Microwave absorption properties of the samples in the Ku band frequency (12.4–18 GHz) were measured with vector network analyzer (VNA, Agilent 8510C) by waveguide method. In this work two types of absorber samples were made:

- Samples containing 45 wt% of each type of doped ferrite.
- Samples containing 45 wt% of a mixture of all three types of magnetic powders (15 wt% of each one).

For this purpose, doped barium hexaferrite powders were uniformly mixed in resin epoxy matrix with weight ratio of 45:55. First, the accurate amount (45 wt%) of powders were added into the resin epoxy and homogenized well with ultrasonic vibration for 5 min, and then, single layer microwave absorber samples were molded in the dimension of $15 \times 7 \times 4$ mm. Table 1 shows related codes of doped samples.

3. Results and discussion

3.1. Phase identification analysis

X-ray diffraction patterns of the substituted samples are performed in order to identify their crystalline phase. As it is clearly depicted in Fig. 1, all the samples exhibit the main characteristic peaks of M-type hexaferrite with magnetoplumbit structure and perfect concordance with the standard JCDPS 007-0276. According to X-ray diffractometry detection limit, no other phases are detected in the diffraction patterns. In all patterns, one can notice weak peak broadening and slight shift of the peaks towards lower angles. These observations may be attributed to the small size of the crystallites and the expansion of the lattice structure by

Table 1
Codes related to substituted samples.

Composition	Sample code
$BaCo_{0.3}Cr_{0.3}Zr_{0.3}Fe_{11.1}O_{19}$	CCZ
$BaZn_{0.3}Cr_{0.3}Ti_{0.3}Fe_{11.1}O_{19}$	ZCT
$BaMn_{0.3}Cr_{0.3}Ce_{0.3}Fe_{11.1}O_{19}$	MCC

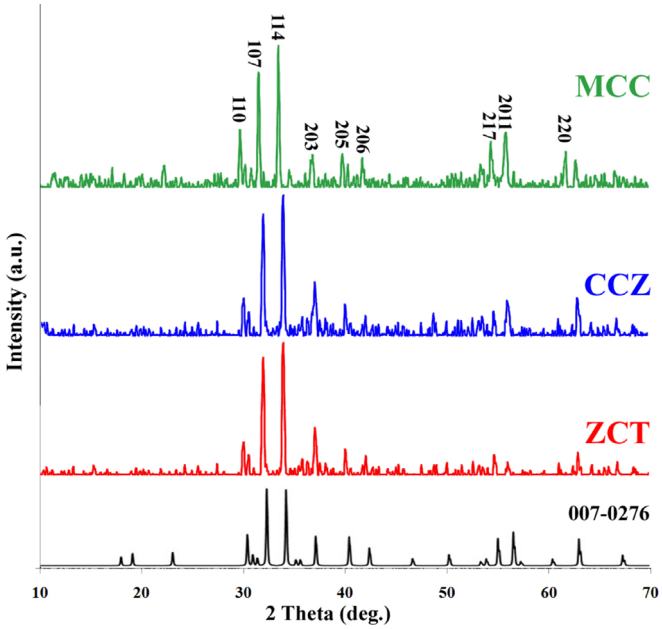

Fig. 1. Diffraction patterns of substituted ferrites.

Table 2
Comparison of unit cell parameters (a, c, c/a, V) of ferrites with corresponding data of pure barium hexaferrite (JCPDS card no. 007-0276).

Sample	$a=b$ (Å)	c (Å)	c/a	V (Å^3)
MCC	6.005	23.676	3.94	739.3
CCZ	5.919	23.410	3.96	710.2
ZCT	5.928	23.394	3.95	712
$BaFe_{12}O_{19}$	5.879	23.117	3.93	691.9

substitution, respectively. In this respect, MCC has the most shift in the position of peaks which can be related to the relatively high ionic radii of cerium and manganese ions. The lattice parameters are also expected to increase with increasing the ionic radii of substituted ions ($Ti^{+4}=0.0745$ nm, $Zn^{+2}=0.088$ nm), ($Ce^{+4}=0.101$ nm, $Mn^{+2}=0.097$ nm), and ($Zr^{+4}=0.086$ nm, $Co^{+2}=0.079$ nm) in comparison with Fe^{+3} ions ($Fe^{+3}=0.0785$ nm). The lattice parameters a and c, and unit cell volume of substituted barium hexaferrite compound can be estimated from the value of d_{hkl} corresponding to the peaks (1 1 4) and (1 0 7), by following formulas [15]:

$$n\lambda = 2d \sin\theta \tag{1}$$

$$\frac{1}{d^2} = \frac{4}{3}\left(\frac{h^2 + hk + k^2}{a^2}\right) + \frac{l^2}{c^2} \tag{2}$$

$$V = \frac{\sqrt{3}\,a^2 c}{2} \tag{3}$$

where (h, k, l), in the above equations, are Miller indices.

The obtained values for all samples are listed in Table 2. Since cerium and manganese ions have the largest ionic radii value among the other variable ions in this case, the severity of change in lattice parameters and cell volume is larger than the other cases. The changes in lattice parameter value represent the rearrangement of these substituting ions in the hexagonal structure to fill the vacancy sites of Fe^{3+} ions. Moreover, it is expected that the change in lattice parameters may affect the exchange interaction