Rare Metal Materials and Engineering
Volume 48, Issue 10, October 2019
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Rare Metal Materials and Engineering, 2019, 48(10): 3108-3112.

ARTICLE

Effect of Nd Content on Microwave Absorption Property of Ce_2Co_{17} Alloy

He Yu[1], Pan Shunkang[1], Cheng Lichun[1,2], Luo Jialiang[1], Yu Jingjing[1]

[1] *Guilin University of Electronic Technology, Guilin 541004, China;* [2] *Central South University, Changsha 410083, China*

Abstract: The flaky $Nd_xCe_{2-x}Co_{17}$ alloy powders were prepared by vacuum arc melting and high energy ball milling method. The influences of Nd content and matching thickness on phase composition, morphology, electromagnetic parameters and microwave absorbing property were studied. The results show that microwave absorption properties of $Nd_{0.3}Ce_{1.7}Co_{17}$ powders are efficiently optimized, the maximum reflectivity (RL) is −32.36 dB and the effective bandwidth is extended by 4 times. Moreover, adjusting Nd content can successfully optimize the absorption properties of Ce_2Co_{17} alloy powder. The absorption peak shifts to lower frequency region with increasing the Nd content, and the maximum RL of $Nd_{0.3}Ce_{1.7}Co_{17}$ powder can reach about −30.53 dB at 7.28 GHz at a given thickness of 1.8 mm with the effective bandwidth of 2.24 GHz, indicating that the Nd-Ce-Co alloy can be used as an ideal absorbing material in C-band with low thickness, broad band and high-efficiency.

Key words: $Nd_xCe_{2-x}Co_{17}$ alloy; electromagnetic parameters; microwave absorbing property

In order to relieve the stupendous electromagnetic pollution ascribed to the explosive increase of electronic devices such as cell phones, computers and laptops, microwave absorbing materials with the advantages of broad band, light weight and high-efficiency microwave absorption property have attracted extensive attention in military defense and civil construction[1-5]. Compared with carbon nanotubes, carbon fibers, perovskite ceramics and various conducting polymers, magnetic materials have become a focus research due to the large loss, wide loss band and easy impedance matching[6].

Traditionally, the absorption strength of electromagnetic wave absorbing materials is a primary factor in estimating microwave absorbing materials. In recent years, the factor has been converted into "thin thickness, light weight, wide band and strong absorption strength"[7,8]. Nevertheless, the application of absorbing materials in microwave frequency band is restricted because of the snoek limit, which is a hindrance to improving the absorbing property of magnetic materials. As reported in the previous researches, flaky shape has lager shape effect, which is beneficial for breaking the snoek limit, resulting in an increase in natural resonant frequency[9,10].

Co-based alloys like Fe-Co-Ni[11], Fe-Co[12] and Ni-Co nanoferrites[13] have been studied to be applied in various frequency bands on account of high Curie temperature, high saturation magnetization, high permeability and low anisotropy. Rare earth (RE) elements have unpaired 4*f* electrons and strong spin-orbit coupling of angular momentum, contributing to optimization of microwave absorbing property[14,15]. In addition, light rare earth elements with double hexagonal lattice or super hexagonal lattice possess low crystal symmetry, generating high magneto crystalline anisotropy[15].

For the sake of outstanding absorbing properties, the effects of Nd content on the phase composition, morphology and electromagnetic parameters of flake-shaped Nd-Ce-Co powders were investigated in this study.

1 Experiment

Typical procedure for the preparation of $Nd_xCe_{2-x}Co_{17}$ (x=0, 0.2, 0.3, 0.4) alloy was carried out by arc melting under the protection of Ar atmosphere, using Nd (>99.99%), Ce

Received date: October 06, 2018
Foundation item: National Natural Science Foundation of China (51361007); Guangxi Key Laboratory of Wireless Wideband Communication and Signal Processing (GXKL06170107); Innovation Project of GUET Graduate Education (2018YJCX87)
Corresponding author: Pan Shunkang, Ph. D., Professor, School of Materials Science and Engineering, Guilin University of Electronic Technology, Guilin 541004, P. R. China, Tel: 0086-773-2291434, E-mail: skpan88@163.com

(>99.99%), Co (>99.999%) as the primary ingredients. And in general, extra 5% Nd and Ce were added on the purpose of compensating the evaporation loss of Nd and Ce. All melted specimens were put into the quartz tube, heat-treated at 800 ºC for 15 d, and then quenched in ice-water mixture. The quenched samples were ground into powders less than 0.1 mm by coarse breaking. To achieve flaky shape powders, the coarse powders were milled for 20 h with the ball-to-powder weight ratio of 15:1 in a planet ball mill (QM-2SP) at the speed of 300 r/min.

The phase composition was measured by X-ray diffraction (XRD) using Cu-Kα radiation within the 2θ range of 20°~80°, and the morphology was analyzed by scanning electron microscope (SEM). The electromagnetic parameters were investigated by a vector network analyzer (VNA), using the toroidal specimens with an inner diameter of 3.0 mm and an outer diameter of 7.0 mm, which were prepared by the mixed process of milled powder and paraffin with the mass ratio of 4:1.

2 Results and Discussion

2.1 Microstructure of $Nd_xCe_{2-x}Co_{17}$ alloy

Fig.1 shows the XRD patterns of the $Nd_xCe_{2-x}Co_{17}$ (x=0, 0.2, 0.3, 0.4, at%) alloy. It can be seen that all samples comprise the Ce_2Co_{17} phase, manifesting that the addition of Nd almost has no influence on the main phase of the alloy.

Fig.2 exhibits the microscopic morphology and particle size of $Nd_xCe_{2-x}Co_{17}$ alloy powders. It is observed that all samples present flake shape after ball milling. According to relevant reports, flaky-shaped structure can generate strong microwave absorption, dominated by multiple scattering caused by larger scattering area[16,17]. The particle sizes for x=0, 0.2, 0.3, 0.4 are about 2.57, 4.72, 4.88, 5.32 μm, respectively, measured using a nano measurer 1.2, indicating an increase an the particle size.

2.2 Electromagnetic parameters of $Nd_xCe_{2-x}Co_{17}$ alloy

Electromagnetic properties of microwave absorbing materials can be expressed by complex permittivity ($\varepsilon=\varepsilon'-\varepsilon''j$) and permeability ($\mu=\mu'-\mu'j'$), standing for the storage capacity and loss ability of microwave absorbing materials[18]. The electromagnetic parameters of $Nd_xCe_{2-x}Co_{17}$ alloy are illustrated in Fig.3. As can be seen from Fig.3a and 3b, the values of the real (ε') and imaginary (ε'') part of complex permittivity increase with increasing the Nd content, probably ascribed to the enhancement of space charge polarization, dominated by the high electrical conductivity caused by the larger surface area of particles with increasing the Nd content[19,20]. In addition, the resonance frequency of ε'' shifts to a lower frequency region,

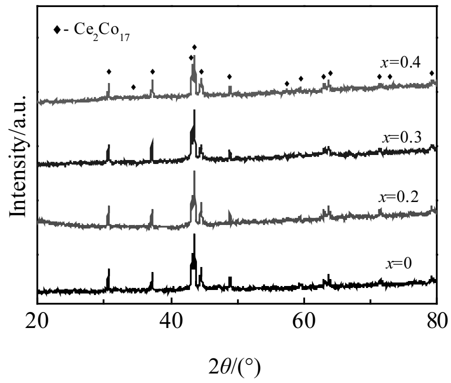

Fig.1 XRD patterns of the $Nd_xCe_{2-x}Co_{17}$ (x=0, 0.2, 0.3, 0.4, at%) alloy

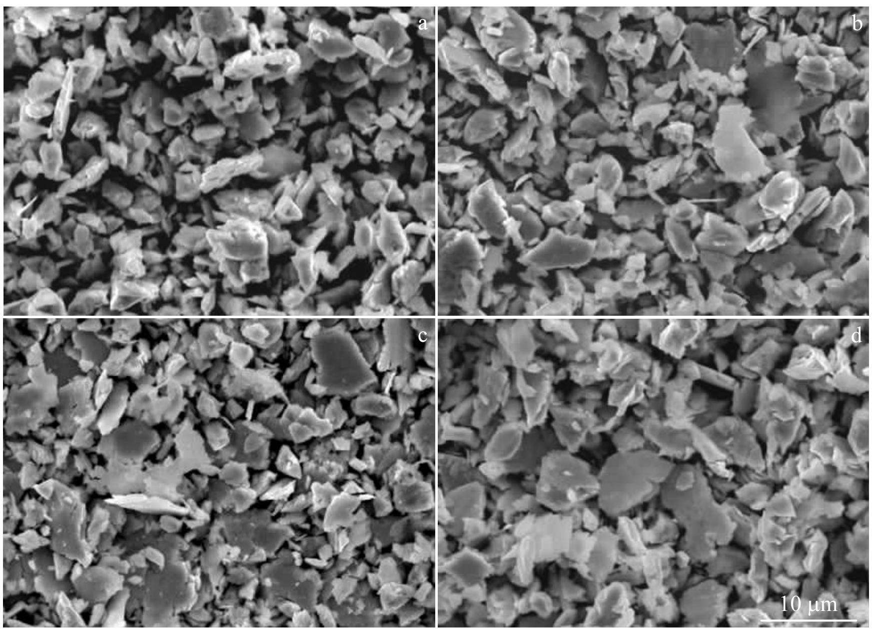

Fig.2 SEM images of the $Nd_xCe_{2-x}Co_{17}$ alloy powders: (a) x=0, (b) x=0.2, (c) x=0.3, and (d) x=0.4

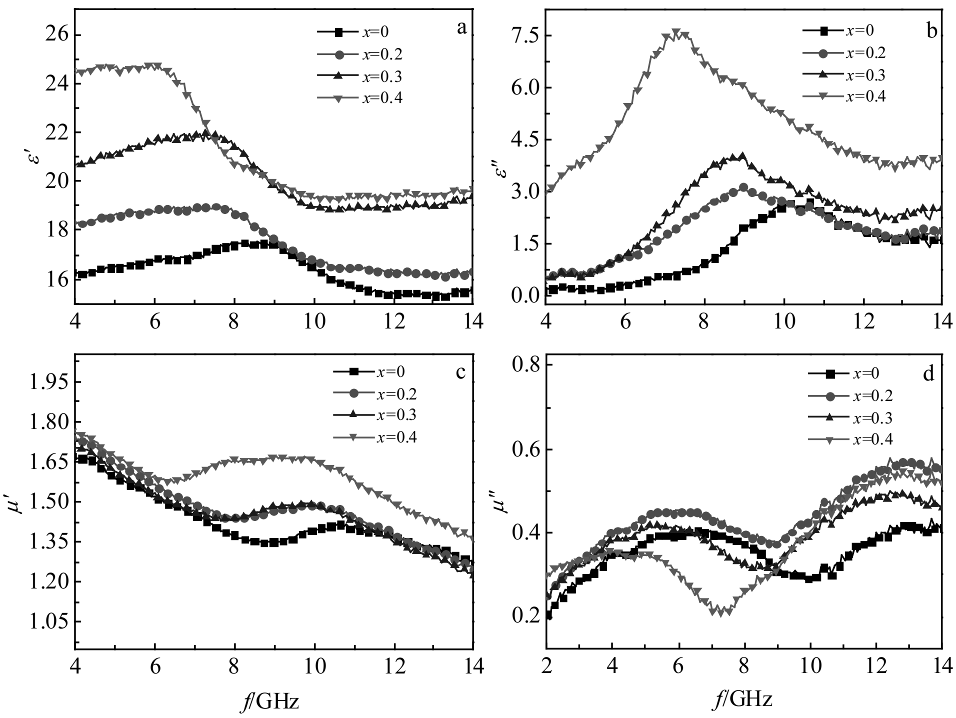

Fig.3 Electromagnetic parameters of Nd-Ce-Co alloy powders with different Nd contents: (a) ε'=0, (b) ε''=0.2, (c) μ'=0.3, (d) μ''=0.4

which may be related to the increase in activation energy. The addition of Nd can generate lattice distortion, and then the average particle size increases, resulting in the increase of activation energy, which is inversely proportional to the resonance frequency of ε''[21]. Thus, the movement of ε'' is attributed to the increase of activation energy with increasing the Nd content.

Fig.3c and 3d show the frequency dependence of the complex permeability for the Nd-Ce-Co alloy powders. As we can see that the resonance frequencies of the real (μ') and imaginary (μ'') part of complex permeability move toward lower frequency region. The values of μ' tend to decrease with the increase in frequency overall, which may be ascribed to the limited speed of spin and domain-wall motion (displacement/rotation)[22]. Furthermore, multiple magnetic resonance peaks for μ'' can be observed distinctly. The first peak may be associated with natural resonance, and the peaks at high frequency may be owing to exchange resonance. Therefore, natural resonance and exchange resonance contribute to magnetic loss[23,24].

2.3 Microwave absorbing property of $Nd_xCe_{2-x}Co_{17}$ alloy powders

The reflectivity (RL) of the specimens for a single layer microwave absorbing material can be calculated by Eq.(1~3) at a given thickness and frequency (2~14 GHz) on the basis of transmission line theory, which is determined by complex permittivity and complex permeability[18,25,26].

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \tag{1}$$

$$Z_{\text{in}} = \sqrt{\frac{\mu}{\varepsilon}}\tanh\left(\text{j}\frac{2\pi fd}{c}\sqrt{\mu\varepsilon}\right) \tag{2}$$

$$\text{RL} = 20\lg\left|\frac{Z_{\text{in}} - Z_0}{Z_{\text{in}} + Z_0}\right| \tag{3}$$

where Z_0 represents impedance of air, μ_0 and ε_0 stand for permeability and permittivity, respectively. f is frequency of electromagnetic wave, d is matching thickness, c is speed of light, Z_{in} is input impedance of the absorber, and μ, ε represent the complex permeability and complex permittivity, respectively.

The reflection loss (RL) (d=1.8 mm) is calculated for the discussion, shown in Fig.4. The maximum absorbing peak slightly shifts to a lower frequency region, which is similar to the regularity of complex permeability and complex permittivity in the range of 2~14 GHz, and the value of reflectivity increases at the first place and then decreases. Combining with Table 1, the bandwidth of $Nd_xCe_{2-x}Co_{17}$ can reach about 2.72 GHz at the given thickness of 1.8 mm with the condition of x=0.2, indicating that Nd-Ce-Co alloy can be endowed with excellent broadband performance at thinner thickness. Furthermore, the $Nd_{0.3}Ce_{1.7}Co_{17}$ alloy can achieve a maximum RL of −30.53 dB at 7.28 GHz and 1.8 mm, manifesting that proper Nd content can optimize the microwave absorbing property in C-band (4~8 GHz). Meanwhile, the bandwidth of RL<−10 dB of $Nd_{0.3}Ce_{1.7}Co_{17}$ alloy powder can also reach about 2.24 GHz, which still has better bandwidth performance. These consequences reveal that precisely choosing Nd content

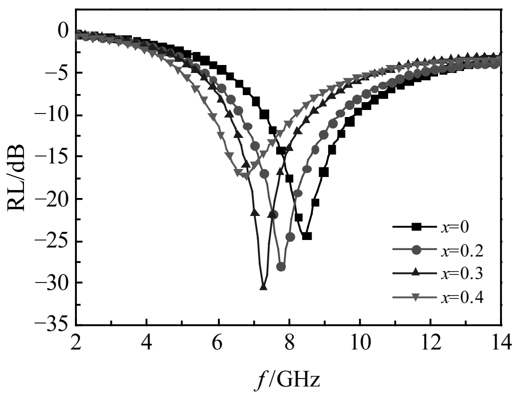

Fig.4 Reflection loss (RL) curves of the $Nd_xCe_{2-x}Co_{17}$ (x=0, 0.2, 0.3, 0.4) alloy powders with different Nd contents

Table 1 Maximum RL and peak frequencies of $Nd_xCe_{2-x}Co_{17}$ alloy

x	0	0.2	0.3	0.4
Maximum RL/dB	−24.29	−28.47	−30.53	−17.25
f_m/GHz	8.48	7.84	7.28	6.72
Frequency width of RL<−10 dB/GHz	2.4	2.72	2.24	2.32

can successfully realize the selective-frequency microwave absorption.

Fig.5 and Table 2 denote the maximum RL of $Nd_{0.3}Ce_{1.7}Co_{17}$ alloy powder with different thicknesses in the frequency range of 2~14 GHz. The absorption peak of $Nd_{0.3}Ce_{1.7}Co_{17}$ powder moves to a higher frequency region with the decrease in thicknesses, shifting from the C-band to X-band, which can be explained by the following equation[27].

$$f_m = \frac{c}{4d_m} \cdot \frac{1}{\sqrt{\varepsilon'\mu'}} \cdot \left(1 + \frac{1}{8}\tan^2 \delta\right)^{-1} \quad (4)$$

where f_m and d_m stand for the matching frequency and thickness, respectively. It is obvious that f_m decreases with

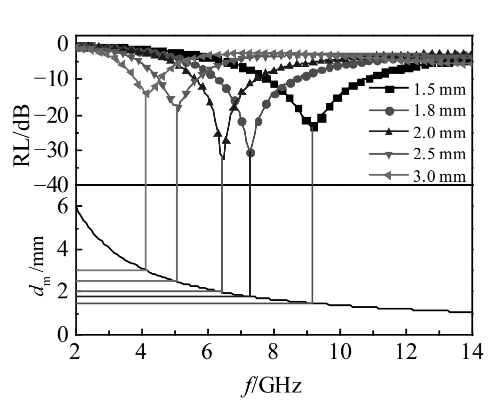

Fig.5 Reflection loss (RL) curves of $Nd_{0.3}Ce_{1.7}Co_{17}$ alloy powder with different thicknesses

Table 2 Maximum RL and peak frequencies of $Nd_{0.3}Ce_{1.7}Co_{17}$ alloy with different thicknesses

Thickness/mm	1.5	1.8	2.0	2.5	3.0
Maximum RL/dB	−23.14	−30.53	−32.36	−17.62	−13.85
f_m/GHz	9.2	7.28	6.48	5.12	4.16
Frequency width of RL<−10 dB/GHz	2.8	2.24	1.76	1.04	0.64

increasing the thickness at a given $\sqrt{\varepsilon'\mu'}$.

As a whole, the effective bandwidth of $Nd_{0.3}Ce_{1.7}Co_{17}$ alloy powder increases by a factor of 4 from 0.64 GHz to 2.8 GHz. The value of reflectivity increases firstly and then decreases with decreasing the thicknesses. The RL of $Nd_{0.3}Ce_{1.7}Co_{17}$ alloy powder can achieve about −32.36 dB (99.94% absorption) at 6.48 GHz with the thickness of 2.0 mm, and the bandwidth of RL<−10 dB is 1.76 GHz. To sum up, the Nd-Ce-Co alloy powder possesses better bandwidth performance and high-effective absorbing property at low thickness, which can be applied in various fields.

3 Conclusions

1) The phase of Nd-Ce-Co alloy mainly consists of Ce_2Co_{17}, manifesting that the addition of Nd has no influence on the phase composition.

2) The bandwidth of RL<−10 dB of $Nd_{0.2}Ce_{1.8}Co_{17}$ powder can be about 2.72 GHz at the matching thickness of 1.8 mm. The maximum RL of $Nd_{0.3}Ce_{1.7}Co_{17}$ alloy powder can reach about −30.53 dB at 7.28 GHz with the effective bandwidth of 2.24 GHz. Moreover, the absorption peak moves towards lower frequency region, under the different Nd contents at a given thickness of 1.8 mm.

3) The absorption peak of $Nd_{0.3}Ce_{1.7}Co_{17}$ powder moves to a higher frequency region with the decrease in thicknesses, shifting from the C-band to X-band. The effective bandwidth of $Nd_{0.3}Ce_{1.7}Co_{17}$ alloy powder increases by a factor of 4, from 0.64 GHz to 2.8 GHz. The maximum RL can achieve −32.36 dB with the best matching thickness of 2.0 mm at 6.48 GHz.

References

1 Chen Shuwen, Tan Guoguo, Gu Xisheng *et al*. *Journal of Alloys and Compounds*[J], 2017, 705: 309

2 Zhou Jia, Zhu Zhenghou, Xiong Chao. *Journal of electronic Materials*[J],2018, 47(2): 1244

3 Zhang Shengen, Zhu Huangxiu, Tian Jianjun *et al*. *Rare Metals*[J], 2013, 32(4): 402

4 Yao Yonglin, Zhang Chuanfu, Fan Youqi. *Advanced Powder Technology*[J], 2016, 27: 2285

5 Cao Maosheng, Han chen, Wang Xixi *et al*. *Journal of Materials Chemistry C*[J], 2018, 6: 4586

6 Li Rui, Pan Canyu, Chi Xiao *et al*. *Chinese Science Bulletin*[J], 2013, 58(36): 3806 (in Chinese)

7 Zhang Yanlan, Wang Xixi, Cao Maosheng. *Nano Research*[J], 2018, 11(3): 1426

8 Zhang Zhaoqi. *Microwave Magnetic and Microwave Absorption Mechanism of FeSiAl Planar Anisotropy Powders Composites*[D]. Lanzhou: Lanzhou University, 2012 (in Chinese)
9 Yang R B, Liang W F. *Journal of Applied Physics*[J], 2013, 113(17): 1
10 Liu Xin, Qiao Liang, Li Fashen. *Journal of Physics D: Applied Physics*[J], 2010, 43: 165 004
11 Duan Yuping, Zhang Yahong, Wang Tongmin *et al*. *Materials Science and Engineering B*[J], 2014, 185: 86
12 Yan Qingbin, Li Shijia, Pang Ernan *et al*. *Materials letters*[J], 2014, 120: 185
13 Chen Biyu, Chen Ding, Kang Zhitao *et al*. *Journal of Alloys and Compounds*[J], 2015, 618: 222
14 Song Jie, Wang Lixi, Xu Naicen *et al*. *Journal of Rare Earths*[J], 2010, 28(3): 451
15 Kang Qing. *New Microwave Absorbing Materials*[M]. Beijing: Science Press, 2006: 146 (in Chinese)
16 Fang Xiaoyong, Cao Maosheng, Shi Xiaoling *et al*. *Journal of Applied Physics*[J], 2010, 107(5): 54 304
17 Katsu Yanagimoto, Kazuhiko Majima, Satoshi Sunada *et al*. *Journal of the Japan Society of Powder and Powder Metallurgy*[J], 2004, 51(4): 293
18 Liu Yi, Li Yunyu, Luo Fa *et al*. *Journal of Materials Science: Materials in Electronics*[J], 2017, 28(9): 6619
19 Liu Jun, Feng Yongbao, Qiu Tai. *Journal of Magnetism and Magnetic Materials*[J], 2011, 323(23): 3071
20 Luo Jialiang, Pan Shunkang, Qiao Ziqiang *et al*. *Journal of Electronic Materials*[J], 2018, 47(1):751
21 Liao Shaobin. *Ferromagnetics*[M]. Beijing: Science Press, 1988: 3 (in Chinese)
22 Zhen L, Gong Y X, Jiang J T *et al*. *Journal of Applied Physics*[J], 2008, 104(3): 34 312
23 Wang Xixi, Ma Tao, Shu Jincheng *et al*. *Chemical Engineering Journal*[J], 2018, 332: 321
24 Ma Junru, Wang Xixi, Cao Wenqiang *et al*. *Chemical Engineering Journal*[J], 2018, 339: 487
25 Lai Yaru, Wang Suyun, Qian Danlin *et al*. *Ceramics International*[J], 2017, 43: 12 904
26 Jiang Fei, Zheng Ji, Liang Lu *et al*. *Journal of Materials Science: Materials in Electronics*[J], 2015, 26: 2243
27 Sun Jun, Xu Huailiang, Shen Yang *et al*. *Journal of Alloys and Compounds*[J], 2013, 548: 18

Nd 元素对 Ce_2Co_{17} 为基体的合金吸波性能的影响

何　煜[1]，潘顺康[1]，成丽春[1,2]，罗家亮[1]，于京京[1]

(1. 桂林电子科技大学，广西 桂林 541004)

(2. 中南大学，湖南 长沙 410083)

摘　要：采用真空电弧熔炼和高能球磨法制备片状 $Nd_xCe_{2-x}Co_{17}$ 合金粉末并且研究了 Nd 含量和匹配厚度对相组成、形貌、电磁参数和微波吸收性能的影响。结果表明，$Nd_{0.3}Ce_{1.7}Co_{17}$ 粉末的最大反射率可以达到–32.36 dB，同时有效带宽能扩大 4 倍。此外，调整 Nd 含量能成功优化 Ce_2Co_{17} 合金粉末的微波吸收性能。随着 Nd 含量的增加，吸收峰有向低频段移动的趋势，并且当厚度为 1.8 mm 时，$Nd_{0.3}Ce_{1.7}Co_{17}$ 粉末在 7.28 GHz 处最大反射率可以达到–30.53 dB，并且有效带宽为 2.24 GHz 中，这表明 Nd-Ce-Co 合金在 C 波段是具有低厚度、宽频和高效等特点的理想吸收材料。

关键词：$Nd_xCe_{2-x}Co_{17}$ 合金；电磁参数；微波吸收特性

作者简介：何　煜，女，1994 年生，硕士生，桂林电子科技大学材料科学与工程学院，广西 桂林 541004，电话：0773-2291434，E-mail: hy944461@163.com