Demonstration of Multi-beam Microwave Heating Based on the Wave Confinement of Hexagonal Photonic Crystal Multilayered Cavity

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Abstract— Multi-beam microwave heating based on the wave confinement of hexagonal photonic crystal multilayered cavity is reported. The proposed hexagonal cavity is formed by alternative layers of alumina (Al_2O_3) and air with the thickness of $0.3a$ and $0.7a$ respectively, where 'a' is the lattice constant. The 17 layer cavity is normally excited with six microwave beams with the peak strength of 1000 V/m. The center of the cavity is loaded with a low loss dielectric and electromagnetic thermal co-simulations are carried out to study the heat transfer due to multi-beam confinement. It is found that characteristic modes of the proposed cavity show the temperature raising rate of 0.77°C/s, 190.26°C/s and 29.52°C/s at 13.855 GHz, 14.54164 GHz, and 14.78175 GHz respectively. This feature is highly useful for arriving the higher temperatures and the creation of plasmas. Particularly, it is anticipated that the proper scaling of the proposed cavity at laser length-scales provide an excellent source of laser beam heating in industrial welding and green photonic solutions.

1. INTRODUCTION

It is known that microwave radiation confers rapid internal heating based on dielectric interactions. Ranging from microwave cooking to industrial heating, microwave heating is an indispensable field. For example, microwave sintering of functional materials such as piezoelectrics and ferroelectrics results in enhanced physical properties [1]. In this regard, attention has been paid to develop the modern microwave furnaces over decades. A typical microwave furnace relies on high power electromagnetic (e-m) field, where an annealing sample is placed at maximum electric field of the radiation. For example, Figure 1 shows the waveguide section of single mode microwave furnace, where a sample will be kept at the maximum electric field position of the waveguide mode. A high power magnetron source (~ 1900 W) is used in such furnaces as one knows that the electric field intensity $|E|$ and dielectric loss determine the efficiency of microwave heating. Similarly, laser radiation is used in welding, but the mechanism is not similar to microwave heating. However, highly intense beams are essential for any electromagnetic wave based heating.

It is interesting to note that the advanced electromagnetic materials such as photonic crystals (PhCs) and metamaterials tailor the propagation of light in an unequivocal ways [2, 3]. The confinement of electromagnetic beams offered by these media is highly useful for indirect heating process [4]. In our recent work [5], we have demonstrated the confinement properties of PhCs for indirect heating through the realization of multilayer photonic cavity. The multilayer cavity confines the mode in a volume comparable to the order of the wavelength and one could explore its mode distribution for heating purpose under single and multi-beam excitations. In this work, we extended our studies to hexagonal multilayer cavity and report its confinement and heating properties under six-beam excitations.

2. PROPOSED HEXAGONAL MULTILAYER CAVITY

Figure 2 shows the proposed hexagonal multilayer cavity for the multi-beam microwave heating. The cavity is made of a one-dimensional multilayer formed by periodic stacking of alumina (Al_2O_3) and air layers with the thicknesses of $0.3a$ and $0.7a$, respectively. Here 'a' is the fundamental lattice constant taken to be 1 cm. The dielectric constant of the alumina layers is 9.0. It is known that alumina is often used as crucible material in heating furnaces and it can withstand high temperatures. The center of the cavity has an area of $1.5\sqrt{3}(0.7a)^2$ and it is filled with air. Hence, the wavelength comparable to this center cavity dimension is expected to excite various e-m modes in it.

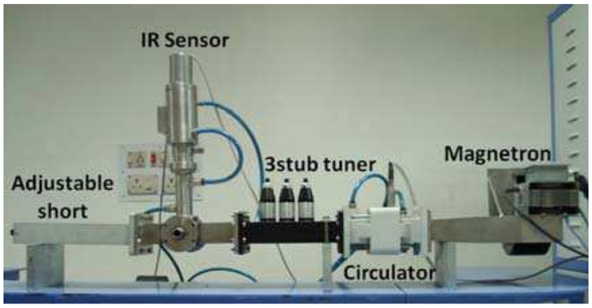

Figure 1: Typical microwave furnace used in sintering process. Here, the maximum electric field position of the waveguide modes is used for microwave heating.

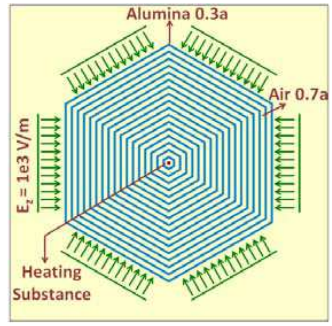

Figure 2: Geometry of the proposed hexagonal multilayered photonic crystal cavity.

3. ELECTROMAGNETIC MODES OF PROPOSED CAVITY

To solve for the electromagnetic modes, full-wave e-m simulations are carried out using commercial electromagnetic solver COMSOL with RF Module. The seventeen layer cavity is excited by six normal incident beams with transverse electric polarization, with the electric field magnitude of 1000 V/m. The sources are excited at 3.78 cm away from the cavity and the waves confined at the center of the cavity are used for microwave heating. Apart from the air-filled cavity, the wave confinement is solved in the presence of a heating substance. For this purpose, a square geometry of dimension 3 mm $\times$ 3 mm is loaded at the center of the cavity. The dielectric property of the heating substance is the same as that of corn oil, which has a dielectric permittivity of $\varepsilon_r = 2.829 - j0.174$. In order to find the resonant mode of the cavity, electric field intensity is integrated over the air regime and heating substance for with and without the presence of heating substance, respectively. Figure 3 shows the resonance spectra and mode patterns for three different resonances.

From Figure 3(a), it is observed that the first resonant mode is shifted to 13.855 GHz after loading the heating substance at the center of the cavity. The corresponding absolute electric field map given at 13.855 GHz reveals that most of field is concentrated at the center of the cavity despite significant losses. The maximum electric field strength available at the center of the heating substance is of the order of 5.79×10^3 V/m. This strength is half of the mode field strength in the absence of the heating substance. It is noted that, comparing to waveguide section, cavities are useful for obtaining higher strengths.

In Figures 3(c) and 3(e), two different e-m modes arising due to the constructive interference of multi-beams are observed. The mode pattern given in Figure 3(d) at 14.54164 GHz indicates that the wave is strongly confined in the multilayer regime of the cavity and at the same time, it witnesses local maxima at the center of the cavity with and without loading the heating substance. For example, without the heating object, the field strength available at the center of the cavity is 1.0369×10^5 V/m, whereas in the presence of heating object, the field strength is computed as 8.9235×10^4 V/m. Such a characteristic mode of the cavity is useful for heating process as it offers the high field strength due to multiple constructive interferences. Similarly, two other characteristic modes of the cavity arising due to the multiple interferences are observed at 14.78175 GHz and 14.7829 GHz for with and without the heating substances, respectively. The absolute electric field map given in Figure 3(e) at 14.78175 GHz reveals the mode filed strength of 3.493×10^4 V/m.

4. RESULTS OF ELECTROMAGNETIC THERMAL CO-SIMULATIONS

In order to reveal the usage of the above confined modes in heating process, e-m thermal co-simulations are carried out using COMSOL. Here the electromagnetic energy absorbed by the heating object is considered as the heat source. Thermal parameters of the heating object and method to solve the coupled differential equations are explained in Ref. [5]. The initial temperature of the heating object is taken as 20°C. Figure 4(a) presents the temperature raising trend of the three different modes. It is found that the object is heated at the rate of 0.77°C/s, 190.26°C/s and 29.52°C/s for three different resonant modes at 13.855 GHz, 14.54164 GHz, and 14.78175 GHz, respectively. It is interesting to note that the characteristic mode of the PhC cavity can yield very high temperatures, in which plasma can be created. For example, the temperature profile shown

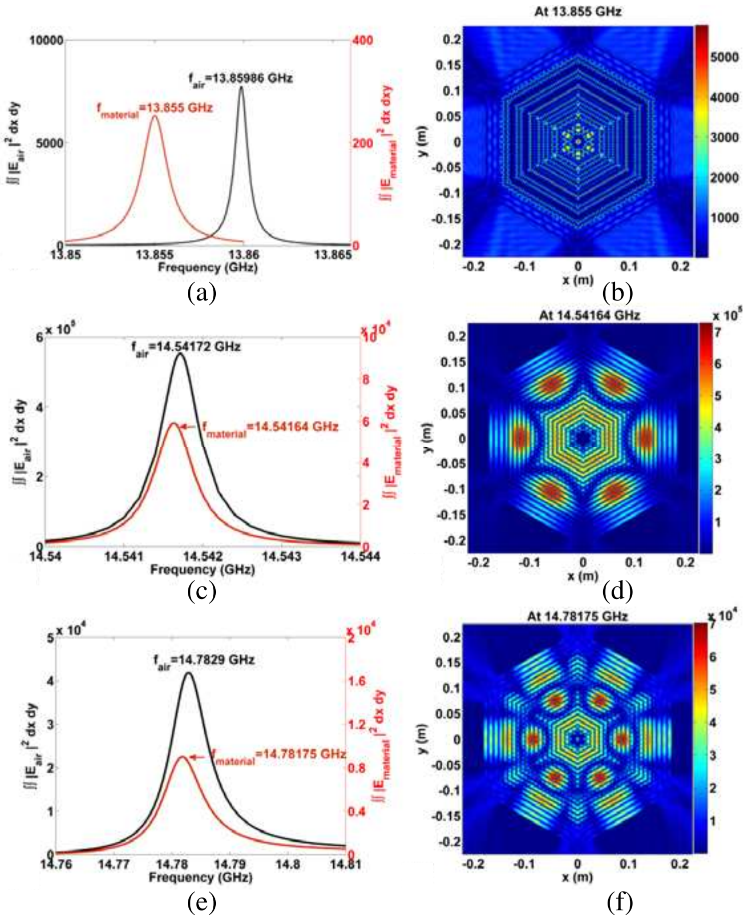

Figure 3: (a), (c) and (e) The resonance spectra of the cavity for with and without the heating substance. (b), (d) and (f) The absolute electric field map for the case of heating object at the center of the cavity at 13.855 GHz, 14.54164 GHz, and 14.78175 GHz respectively.

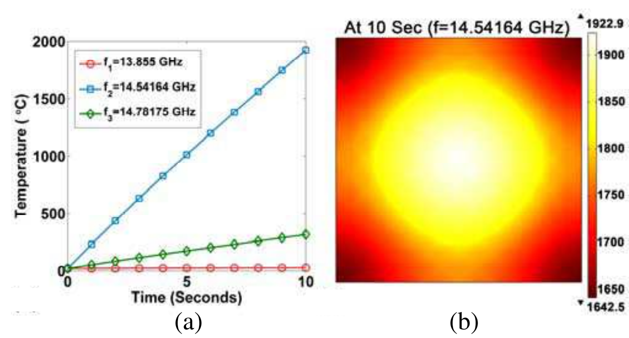

Figure 4: (a) Temperature raising rate for three different cavity resonance modes. (b) Temperature profile at 5 s for the resonance mode of 14.54164 GHz.

in Figure 4(b) at 14.54164 GHz shows a temperature rise of 1923°C in five seconds for six beam excitations. The heating reveals the Gaussian type distribution, which is the direct map of the mode pattern of the cavity.

5. PERSPECTIVES AND CONCLUSIONS

We have demonstrated the multi-beam microwave heating using a hexagonal multilayered photonic crystal cavity. The present work demonstrates various confined modes of the cavity for efficient heat transfer applications. With the proposed cavity, one can achieve very high temperatures at the rate of 190.26°C/s using six beams excitations with the input electric filed strength of each beam to be 1000 V/m. Comparing to our earlier studies on C_4 symmetric cavity [5], we have observed that besides the multi-beam excitations, the corners present in the cavity results in more losses. Moreover, the cavity space available for the heating substance is very small and this will result in higher operating frequency. In our future work, we plan to extend this present study to third-dimensions so that out-of-plane radiation losses could be evaluated. Moreover, incorporating the other heating mechanisms such as convection process will give additional insights to the present problem. Since periodic structures are scalable to any frequencies, we anticipate that the present work will be useful for other heating mechanism including laser light and visible frequency confinements.

ACKNOWLEDGMENT

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