MIT Department of Nuclear Science and Engineering

Thesis Prospectus
for the
Bachelor of Science Degree
in
Nuclear Science and Engineering

Design, Fabrication, Testing, and Application of a Sub-Wavelength Microwave Lens

[redacted]

1. Introduction

The process of crushing and grinding rocks for mining (called comminution) is very energy-intensive. It is estimated that somewhere between 3-5% of the world's electricity is used for comminution in various industries [1]. In the US, 1.5% of electricity generation is used in such material size reduction processes [2]. The current mechanical methods employed are highly inefficient and expensive, with efficiencies less than 1% [1, 2]. Given the amount and scale of mining operations worldwide, making this process more energy efficient would both reduce electricity consumption and save money.

One novel approach to improving comminution is using microwaves to rapidly heat certain minerals within the rocks before crushing or grinding. This creates thermal stresses large enough to cause microcracks along grain boundaries in the rocks. Studies have shown that microwave heating increases the grindability by up to 70% [3]. The microcracks decrease the structural integrity of the rock, allowing it to be mechanically crushed using much less energy. These effects have been well examined for many types of minerals [3–7]. It has been found that this effect is increased by using higher power densities, which in turn require less microwave energy input. Smaller rocks have been shown to require more energy to achieve the temperatures necessary for sufficient thermal stresses. A shorter pulse length is also more effective since it results in larger temperature gradients between the target minerals and the surrounding material [3].

Previous work in this area has primarily focused on the use of a microwave cavity to create standing waves [2]. The rock is placed in the microwave cavity for heating. This approach is problematic because it limits the size of rocks which can be heated to a few centimeters, which is not practical for an industrial-scale mining operation. Microwave cavities are also typically made of materials which could easily be damaged from the harsh environment in mines [3]. Corrosion and other material damage over time would severely limit the lifetime of these devices, making them less desirable for use in industrial-scale operations. The level of microwave energy input is another major set-back for this approach. High power sources are not always available at desired frequencies or useable in an industrial setup. Additionally, requiring higher energy inputs reduces energy efficiency gains. The lens described in this work is an attempt to address these issues through novel design and provide a usable technology for industrial-scale microwave-assisted comminution.

2. Objective

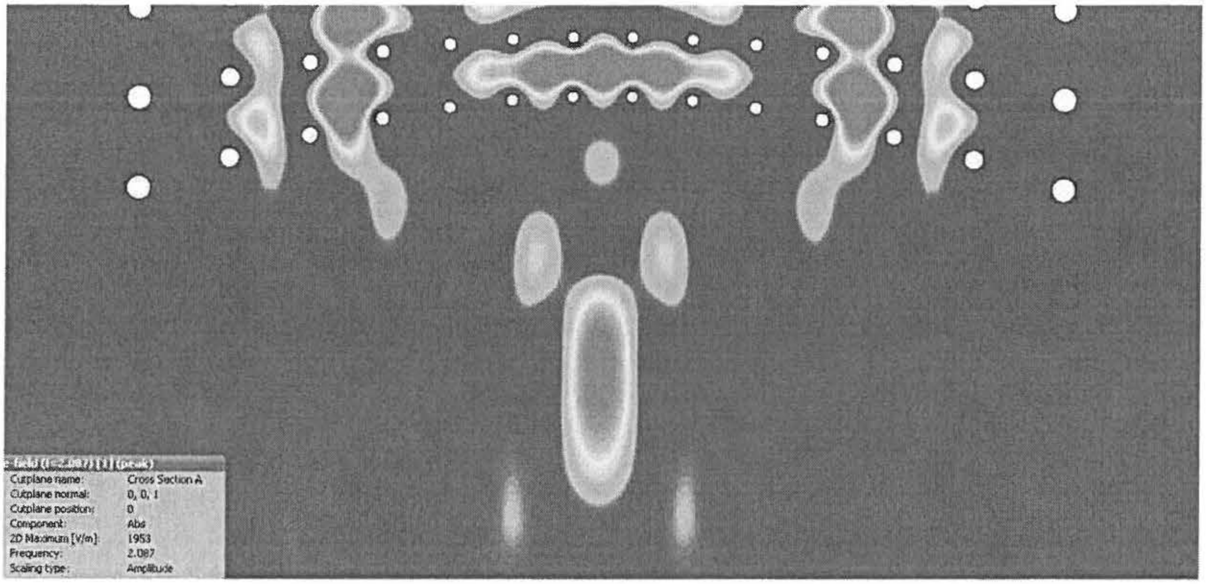
The main objective of this work is to design, build, and test a photonic band gap (PGB) lens for applications in microwave-assisted comminution. PBG devices are designed to exploit gaps in allowed wave frequencies (band gaps) in order to confine some wave modes while allowing others to escape. Using sub-wavelength focusing, the lens is able to beat the diffraction limit of a conventional lens. This leads to a higher power density which in turn reduces the necessary microwave energy input. The lens does not require a microwave cavity for operation, so the setup could be scaled for use on large rocks. The microwave source with this device would be pulsed, leading to very short heating times and higher thermal stresses. The design of this lens will be optimized to achieve the maximum possible power density in the focal spot. The optimized design or designs will be built and tests will be performed in order to validate the simulations.

If time allows, this work will also contain an analysis of the economics of microwave-assisted comminution and what level of energy savings this PBG lens could create if implemented. This study would also examine how the lens could be incorporated into existing mining comminution circuits. Time permitting, a journal article will be written on this work.

3. Method

The PBG lens design will be optimized using CST simulations. In these simulations, the geometry of the structure is varied in order to find the sizes with the highest power density. This will be done first for a quasi-2D geometry of the lens, with rods less then 5 mm in axial height. The spacing at the center of the lens between rods is 65 mm center-to-center, and the sizes and spacings of the rods are determined by an adjustable formula. An example result is shown in Fig. 1. This structure will be built using conventional machining processes and tested on a vector network analyzer (VNA) with a probe signal. After obtaining the results of these tests, the design will be revisited and adjusted before building the full 3D structure. Various fabrication methods for the 3D structure—including 3D printing using direct metal laser sintering (DMLS) or electroplating—will be examined before one is chosen. Similar tests will be performed on the 3D structure to evaluate its performance.

The engineering study into this device would involve calculating the energy usage of this lens and comparing it against the energy savings it brings. These calculations would be framed against the numbers for existing comminution circuits. The study would also examine how this lens could be incorporated into existing setups, ideally allowing the removal of some inefficient equipment. From this information, the study would explore possible carbon emissions savings from using this lens and microwave-assisted comminution.



field (f=2.087) [1] (peak)

Cutplane name: Cross Section A
Cutplane normal: 0, 0, 1
Cutplane position: 0
Component: Abs
2D Maximum [V/m]: 1953
Frequency: 2.087
Scaling type: Amplitude

Figure 1: Example results of a CST simulation of the 2D structure. The white circles are the cross-sections of the PBG rods. The colors show the absolute magnitude of the electric field at the peak power frequency of 2.087 GHz. The focal spot can be scene in the bottom center, where the light blue edges are the location of 1/e of the peak E-field.

4. Task Schedule

Dates listed for the engineering study and journal article are tentative, pending adherence to the design and testing schedule.

Task	Date of completion
2D design optimization	11/12/14
Drawings and fabrication order (2D design)	11/17/14
2D design cold testing	12/19/14
Begin writing thesis	12/21/14
3D design optimization	01/16/15
Drawings and fabrication order (3D design)	01/21/15
3D design cold testing	02/27/15
Investigate economics and implementation	03/27/15
First rough draft of thesis	03/28/15
First draft of journal article	04/03/15
Second rough draft of thesis	04/10/15
Final draft of journal article	04/17/15
Final draft of thesis	Thesis due date: 05/08/15

5. References

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[2] D. Whittles, S. Kingman, and D. Reddish, "Application of numerical modelling for prediction of the influence of power density on microwave-assisted breakage," *International Journal of Mineral Processing*, vol. 68, pp. 71–91, 2003.

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[4] T. Chen, J. Dutrizac, K. Haque, W. Wyslouzil, and S. Kashyap, "The relative transparency of minerals to microwave radiation," *Canadian Metallurgy Quarterly*, vol. 23, no. 1, pp. 349–351, 1984.

[5] S. Kingman, "The effect of microwave radiation on the comminution and beneficiation of minerals and ores," Ph.D. dissertation, University of Birmingham, 1998.

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[7] S. Kingman, W. Vorster, and N. Rowson, "The influence of mineralogy on microwave assisted grinding." *Minerals Engineering*, vol. 13, no. 3, pp. 313–3227, 2000.

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