Design of the Quasi-Optical Transmission Line for Millimeter Wave Deep Drilling

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Abstract: *A 45GHz quasi-optical transmission line with three quasi-optical mirrors for millimeter wave deep drilling is designed and experimental tested. Based on the technique of Gaussian beam transformation, the proposed optical transmission line, which consists of three mirrors, is investigated and optimized by vector analysis of the fields on mirror surfaces. The synthesis method has been verified to transfer the electromagnetic wave from the MOU to the specified position of the sample to be heat. The numerical results show that the power transmission efficiency is over 95%. The experimental results demonstrate the output pattern at the position of rock is a good agreement with the desired fundamental Gaussian mode and the output power density of 1.65 kW/cm^2 at the heated rock surface meets the preliminary requirements to melt the rock.*

Keywords: Gyrotron, Vector diffraction theory, geometrical optics, Gaussian beam

Introduction

Compared with the conventional drilling methods such as flame jets, plasma discharges, steam lances and infrared laser beams, the advantages of MMW directed energy include lower costs of penetrating and the possibility of drilling into deep hot hard rock to access geothermal heat. The literature [1] shows that millimeter-wave (MMW) directed energy from a gyrotron could make full-bore thermal penetration into hard rock a practical reality. Woskov[1] used the waveguide transmission line to transmit the mm-wave to the drilling face and the working face rock is heated to vaporize it. However, in this paper, we develop the optical transmission line to transmit the linearly polarized Gaussian beam to heat rock sample.

Numerical and simulation aspects

The scheme of the designed quasi-optical transmission line system with a very high power conversion efficiency is shown in Figure.1. Prototype gyrotron operating at 45GHz with output power continuously tunable (0-20kW). The main components of the optical transmission line system going from the gyrotron to the rock sample can be described as follows. First, the Gaussian beam from the gyrotron enters the MOU. Then the beam passes through three mirrors for transmission and focusing. Finally, the Gaussian beam with the intense millimeter wave penetrated the rock sample.

In order to obtain the shape of the quasi-optical mirror, the radiation field was calculated using the vector diffraction theory according to the Stratton-Chu equations [3]:

$$\vec{E}' = \frac{1}{4\pi jw\varepsilon}\iint[k^2(\vec{n}\times\vec{H})G + (\vec{n}\times\vec{H})\cdot\nabla(\nabla G) + jw\varepsilon(\vec{n}\times\vec{E}\times\nabla G)]dS \tag{1}$$

$$\vec{H}' = \frac{-1}{4\pi jw\mu}\iint[k^2(\vec{n}\times\vec{E})G + (\vec{n}\times\vec{E})\cdot\nabla(\nabla G) - jw\mu(\vec{n}\times\vec{H}\times\nabla G)]dS \tag{2}$$

$$G = \frac{e^{-jkR}}{R} \tag{3}$$

Where $\vec{E}$, $\vec{H}$ are the electric and magnetic field vectors at the output of the MOU. G is the green function. μ is the permeability, ε is the permittivity, R is the distance between different positions.

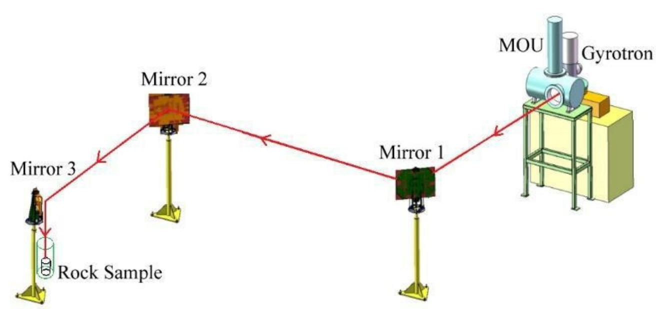
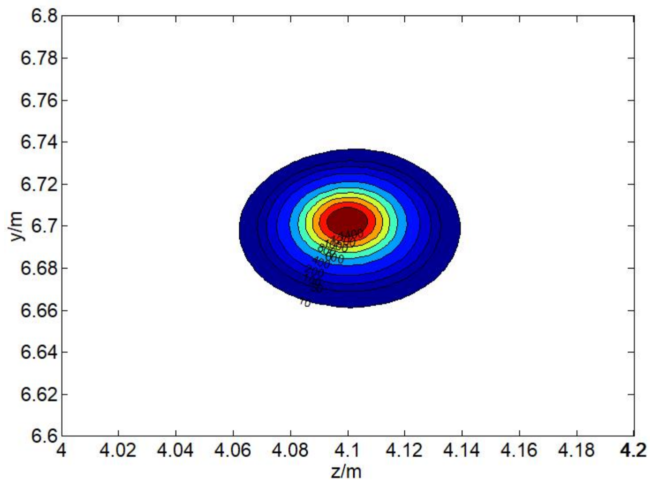


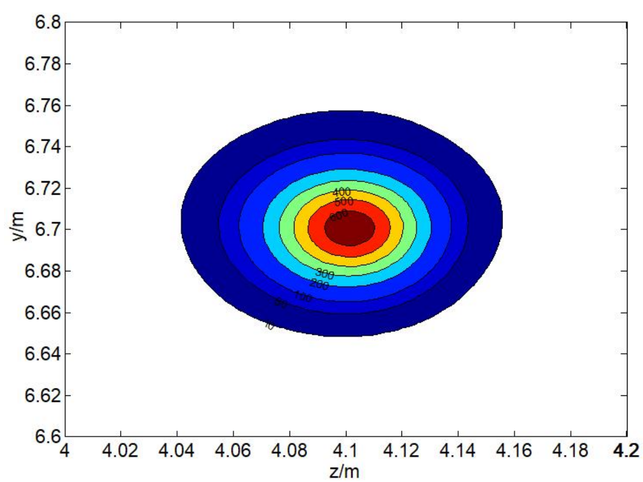
Figure.1. Layout of the 45GHz quasi-optical transmission line system for the intense MMW rock exposure

Usually, the method for the synthesis of such adapt phase-correcting mirrors are based on the scalar analysis [2] of the field on mirror surfaces. In order to transfer the energy output from gyrotron to the sample as lossless as possible, one synthesis three mirrors by vector analysis method [3] and the surface contours of the mirrors are iteratively optimized in terms of the Katsenelenbaum-Semenov Algorithm (KSA).

The calculated output power distributions on different positions from the third mirrors as a heating source is presented in Figure.2. In order to save space, Fig.2 shows only the power distribution of Gaussian beam at 500mm and 800mm from mirror 3. In order to clearly observe the distribution of power density, we mark the equal power density line in Figure 2. Analyzing the numerical result, we can get the maximum power density is 1650W/cm^2 in Fig. 2(a) when the output power of the gyrotron is 15 kW and the position of calculated power distribution is 500mm away from mirror 3. In case of the constant output power, we placed the rock at a distance of 800mm from the mirror 3, the power density is 668W/cm^2. According to the calculations, the farther the distance between the effector and the mirror, the lower the power density at the center of the output beam. In order to achieve the energy required for the rock to melt, the rock is fixed at 500mm from the last mirror.



(a)



(b)

Figure.2. Calculated power distributions of the electric field at the different distance from the mirror 3 (a) Power distribution at 500mm from the mirror 3. (b) Power distribution at 800mm from the mirror 3

Experiment result

The quasi-optical transmission system has been assembled and the preliminary test of laboratory experiment is carried out. Real-time monitoring of the experiment is presented in Fig.3. When that rock sample with peak intensities of 1-2 kW/cm^2 can be melted and vaporized over 2000 °C in a few minutes [1]. From the Figure.3, we can see sample rock burns and melts by high-power millimeter wave within the scope of Gaussian like shape.

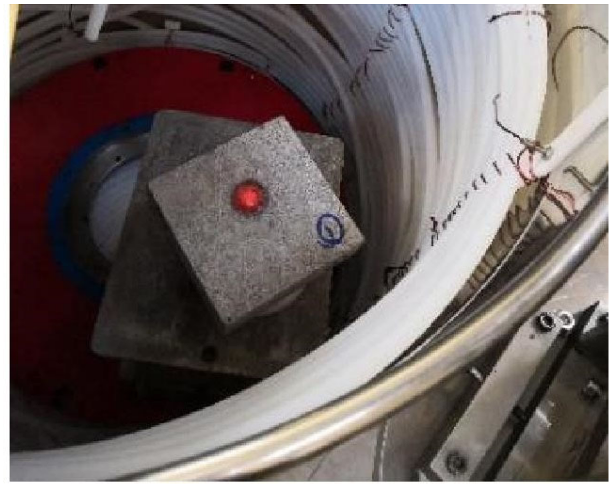


Figure.3. Rock sample being heated by millimeter wave at 500mm from the mirror 3

Conclusion

The three mirrors of a 45GHz quasi-optical transmission line with high power transmission efficiency for the millimeter wave deep drilling is successfully designed and tested. Based on the analysis method, a mirror optimization algorithm for the three quasi-optical mirrors has been develop to achieve a high transmission power efficiency with 95% and the shape of the three mirrors has been optimized. The experimental results indicate that a good agreement between measurement and theoretical prediction is obtained and the output power density of 1.65 kW/cm^2 at the heated rock surface meets the preliminary requirements to melt the rock.

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