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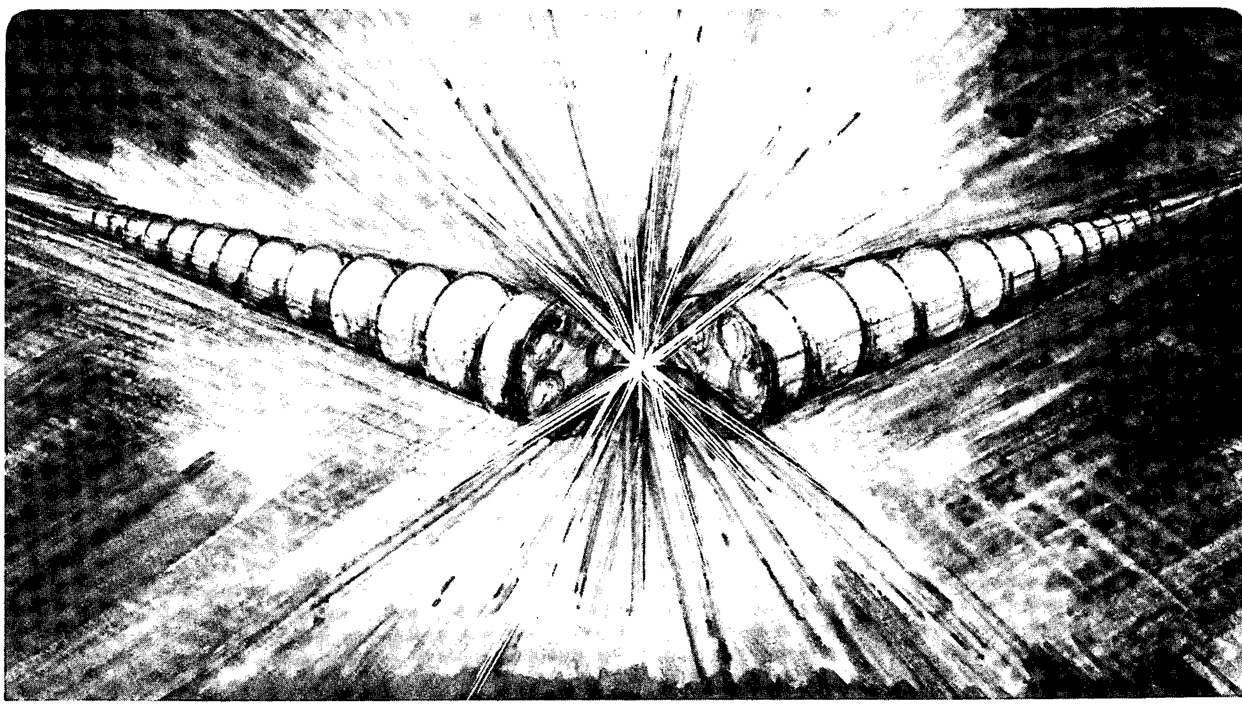

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Introduction

The Infrared Free Electron Laser (IRFEL) for the proposed Chemical Dynamics Laboratory at Lawrence Berkeley Laboratory will operate from 3 - 50 μm and use all-metal optics. This choice of optics allows for broad tuning and has excellent power-handling capabilities. A hole-coupling approach for the optical resonator was adopted after extensive computer simulations [1] verified that it fully met the design requirements.

To bench-test the simulations we have carried out a scaled cavity experiment utilizing a visible (632.8 nm) continuous wave (CW) HeNe laser. Two cases have been studied: a) a Gaussian near-concentric symmetric resonator and b) a hole-coupled resonator with degenerate higher order modes. The simple geometry of the former case allows for a direct comparison with analytical theory and is useful for bench marking the diagnostic equipment. Since mode degeneracy should be avoided for good operation of an FEL, gaining an understanding of the latter case is important. Furthermore, it provides a good test case for evaluating the code performance.

After discussing the theoretical model used in the simulations, we describe the cavity parameters and the experimental set-up. We proceed by comparing, for both case a) and b), the experimental results with theoretical predictions and simulations. This is followed by the summary and conclusions of these experiments.

2. Theoretical model

The simulations have been carried out with the code HOLD [1] which has been modified to allow for external continuous injection of wave fronts into the cavity. The modification was made necessary by the use of a CW HeNe laser in the experiment. The code first calculates the properties of a self-consistent mode-profile after injecting a single wave front into a specified cavity and determines the necessary waist size, waist location and radius of curvature of the injected mode to match to the lowest order cavity mode. This is called the transverse modematching. After the user has specified the injected mode properties, the code calculates the mode profiles and the optical power at the beamsplitter locations and both mirrors. For a given complex injected electric field profile, E_{in}, the complex intra-cavity field profile, E_c, can be obtained from

$$E_c = \frac{E_{in}}{1 - e^{j2k(L+\delta L)}M} \tag{1}$$

Here k is the usual wave number, M is the complex transfer matrix, and δL is a cavity length adjustment. Adjusting the phase advance $k\delta L$ for maximum power is called longitudinal mode matching. The code can optimize both the transverse and longitudinal mode matching through iteration.

3. Scaled Cavity Parameters and Experimental Set-up

The design of the IRFEL calls for an optical cavity length, L, of 24.6 m, a Rayleigh range, z_R, of 1 m (hence a radius of curvature for the mirrors R of 12.38 m) resulting in a stability parameter, g, of -0.987. In scaling from the IR to visible wavelengths we have chosen to increase g to -0.8 for the following reason: mirror misalignment by an angle θ_M leads to a change in the angle of the optical axis, θ_{OA}, given by $\Delta\theta_{OA} \cong \frac{\Delta\theta_M}{1+g}$. To keep the optical axis within 1/10 of the mode rms angle $\sigma = \left(\frac{\lambda}{2\pi L}\right)^{1/2}\left(\frac{1-g}{1+g}\right)^{1/4}$ requires a pointing accuracy of 0.6 μrad for g = -0.987 and 9.5 μrad for g = -0.8. Although the higher pointing accuracy can be achieved, in our present set-up we are limited to about 10 μrad. The radius of curvature R was chosen to be 0.75 m and hence, for g = -0.8, we obtain L = 1.35 m, a waist size w_o of 213 μm and z_R = 0.225 m. The ratio of cavity length to wavelength is 2.46 x 10^6 for the IRFEL cavity which is reasonably close to 2.13 x 10^6 for the scaled cavity.

The CW HeNe had an output power of 1.54 mW and was feedback stabilized against frequency drift to within ± 25 MHz of the centerline at 632.81642 nm. Since the free spectral range is 111 MHz, this frequency drift can give rise to a substantial uncontrolled longitudinal mismatch . Future studies will utilize a CW HeNe stabilized to within a part in 10^{10}. Cavity mirror vibrations will then become the main source of longitudinal dephasing between the injected and cavity mode. In the present experiment, the resonator power spikes due to longitudinal mismatch from vibrations and frequency instability of the injection laser. In fact, during cavity resonance in the experiment, the frequency locker on the stabilized HeNe indicated optical feedback into the laser resonator which causes "frequency pulling". Unambiguous results were achieved by looking at the maximum power points.

The experimental lay-out is shown in Fig. 1. A P-polarized beam was injected into the cavity using the uncoated side of a plane parallel beamsplitter (BS1). The other side of the beam splitter was anti-reflection (AR) coated to minimize cavity losses. The transverse properties of the injected mode were controlled through the use of a three-lens telescope, allowing for good flexibility in adjusting both spot size and radius of curvature of the phase-fronts at the injection point.

The cavity performance was monitored using a second intra-cavity beamsplitter (BS2) with the AR-coated side sampling the intra-cavity mode and the uncoated side sampling the intra-cavity power. The optical power was measured by monitoring the output of a calibrated silicon diode on a 250 MSample/s digital oscilloscope. Both the intra-cavity and out coupled mode-profile were measured using a CCD camera, with 19 μm/pixel spatial resolution, connected to an 8 bit framegrabber board, with a system dynamic range of about 100.

Control of mode degeneracy requires an adjustable aperture in front of the mirrors. For the IRFEL, when operating in the wavelength range of 6 - 13.7 μm, the design values of the aperture radius, a, and outcoupling - hole radius, b, will be 30 - 50 mm and 2.8 mm respectively. The resonator Fresnel numbers $N_a \equiv \frac{a^2}{L\lambda}$ and $N_b \equiv \frac{b^2}{L\lambda}$ are, for the IRFEL operating specifically at λ = 12 μm: N_a = 5.42 (using a 40 mm aperture) and N_b = 0.0266. To match resonator Fresnel number we have used an aperture radius of a = 2.17 mm and a hole radius b = 150 μm for the scaled cavity experiment. The ratios of spot size on the mirror, calculated from Gaussian optics, to aperture and hole size determine both the diffraction losses and the outcoupling efficiency. Since the mirror spot sizes are quite different for the IRFEL design cavity and the scaled cavity, they have significantly different cavity losses for the lowest order mode.

In order to obtain an estimate for the cavity losses, the reflectivity of each optical surface was measured. Through visual inspection with a microscope, the roundness of the laser drilled hole in the outcoupling mirror was found to be excellent . However, a 100 - 150 μm wide zone around the hole showed structure which causes diffuse scattering of the incident laser beam. Measuring the power in the incident and transmitted beam and the power in the beam reflected into the acceptance cone of the second cavity mirror, the reflectivity for the mirror with hole was found to be 94.5 % ± 0.5% , compared to 99.8 % for the mirror without hole. Therefore, lower order modes see a higher loss on this non-ideal surface than expected from the hole size. In conclusion, both the smaller spot size, due to increasing the stability parameter from -0.987 to -0.8, and the non-ideal reflectance of the mirror, have increased the losses for the lowest order mode, so that mode degeneracy is achieved in the scaled cavity experiment. We next discuss the experimental results for both the Gaussian case and, in greater detail, the degenerate hole coupled case.

4. Results for Gaussian Cavity

Using Gaussian beam propagation theory, the three-lens telescope was designed to mode match the HeNe laser beam into the cavity. At the observation point, located 59.3 cm from one of the resonator mirrors, the measured injected and cavity beam spot size were 229 µm and 225 µm respectively. This is to be compared to the calculated cavity spot size of 227 µm. The measured peak intra-cavity power was 8.99 mW, which is in excellent agreement with the 9.19 mW predicted by HOLD. Using the simplified expression for the peak circulating intensity in a purely passive cavity from Siegman [2], $\frac{I_{circ}}{I_{inj}} \approx \frac{4\delta_1}{(\delta_1 + \delta_2 + \delta_0)^2}$ we obtain $\frac{I_{circ}}{I_{inj}} \approx 5.83$ or P_{ic} = 8.98 mW for P_{inj} = 1.54 mW. Here $\delta_{1,2}$ are the losses on the two cavity mirrors and δ_0 contains all losses due to the beam splitter surfaces. As expected, the resonator power spiked with spikes lasting typically for a few milliseconds. Both periodic and aperiodic spikes were observed which will be the subject of further study.

5. Results for Degenerate Hole Coupled Cavity

As discussed in the previous section, in the experiment we used a 300 µm diameter hole in one of the mirrors (from here on referred to as the RH-mirror), and placed a 4.34 mm diameter iris 1 cm in front of the second mirror (from hereon referred to as the LH-mirror) for transverse mode profile control. The same hole size was used in the simulations but the iris was put on top of the LH-mirror by specifying the mirror diameter to be 4.34 mm. The measured surface reflectivity's, cavity dimensions and properties of the injected beam were used as further input to HOLD.

The power spikes caused by uncontrolled longitudinal mismatching were found to typically last about 5 - 10 ms, which is longer than in the previous case. Similar to the previous case, periodic and aperiodic resonator power oscillations were observed (Fig. 2) which will be studied more closely in the future. The measured peak intra-cavity power, P_{ic}, and peak hole-outcoupled power, P_{oc}, were 0.182 mW and 8.7 μW respectively. The simulations predicted P_{ic} and P_{oc} to be a factor of two lower than the measured values. This small discrepancy will be carefully reconsidered.

In Fig. 3 we show line-outs of the axially symmetric intracavity profiles for the left and right propagating wave fronts as measured by the CCD camera. To ensure that the cavity mode profile was captured close to a peak in the resonator power, a sequence of images was grabbed after a trigger signal was sent to the framegrabber board. As seen from the two rings around the central peak, the cavity was resonating in a second order mode. The calculated mode profiles (Fig. 4) agree well with the measured profiles except for the amplitude of the rings in the right going profile at location 6 (see Figs. 3 and 4). This discrepancy may be caused by the large Fresnel number involved in the mapping procedure at that location.

The experimental evidence for mode degeneracy is shown in Fig. 5. At a same location, the resonator mode oscillated back and forth between the two shown mode profiles. The simulation results indicate that the modulus of the cavity mode eigenvalue of the first five modes is similar, i.e. they have similar roundtrip cavity losses. However, the eigenvalue phase is different. Small changes in longitudinal mode matching can then cause the observed mode jumping [1]. Finally, as can be seen from Figs. 6 and 7, good agreement is obtained between the outcoupled mode profile from the experiment and simulation.

6. Summary and Conclusions

The main purpose of the experiments presented in this paper was to evaluate the performance of the code HOLD . The results of two experiments were presented and a comparison was made with simulations. Both experiments involved the injection of a CW-HeNe laser into a stable cavity. In the first experiment a Gaussian near-concentric symmetric resonator was used, allowing straightforward bench marking of all diagnostics because all measurable quantities can be verified with analytic theory. Excellent agreement between experiment and both analytic theory and simulation results from the code HOLD was obtained for the mode profiles and intra-cavity power.

In the second experiment we looked at a hole-coupled resonator. Due to the particular choice of stability parameter, outcoupling hole size and intra-cavity aperture size, mode-degeneracy was observed as evidenced by an intra-cavity mode profile which alternates between two higher order modes. Measurements of intra-cavity and outcoupled mode profiles and optical power agreed reasonably well with calculated mode profiles. As for the case of the Gaussian resonator, power spikes occurred due to uncontrolled longitudinal matching, with both a periodic and aperiodic character. Future experiments will concentrate on improving the injection laser stability, suppression of cavity mirror vibrations and better pointing accuracy to allow a study of the design parameters for the proposed IRFEL.

7. Acknowledgments

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References

[1] M. Xie and K.-J. Kim, Nucl. Instrum. Methods **A304**, 792 (1991); M. Xie and K.-J. Kim, in Proceedings of 13th International FEL - Conference, Santa Fe, New Mexico (1991).

[2] A. E. Siegman, "Lasers", University Science Books, Mill Valley, California (1986).

Figure Captions

Figure 1: Set-up of the scaled cavity experiment.

Figure 2: Measured intracavity power as a function of time showing periodic and aperiodic fluctuations.

Figure 3:Measured intra-cavity mode profiles for the left and right propagating wavefronts. The cavity lay-out shows the location at which the measurement was made.

Figure 4:Calculated intra-cavity mode profile for the left and right propagating wavefronts. The number next to some of the profiles denotes the corresponding experimental profile at that location shown in Fig. 3.

Figure 5:Plot of two intra-cavity mode profiles 396.3 mm away from the mirror with hole, taken at different times. This behavior is consistent with mode degeneracy as verified by simulations.

Figure 6: Measured outcoupled mode profile at different locations (c). The location at which the outcoupled modes have been measured is depicted in (a). The profile at z = 148.4 cm and a Gaussian fit are shown in (b).

Figure 7: Calculated outcoupled mode profiles, at same locations as in Fig. 6.

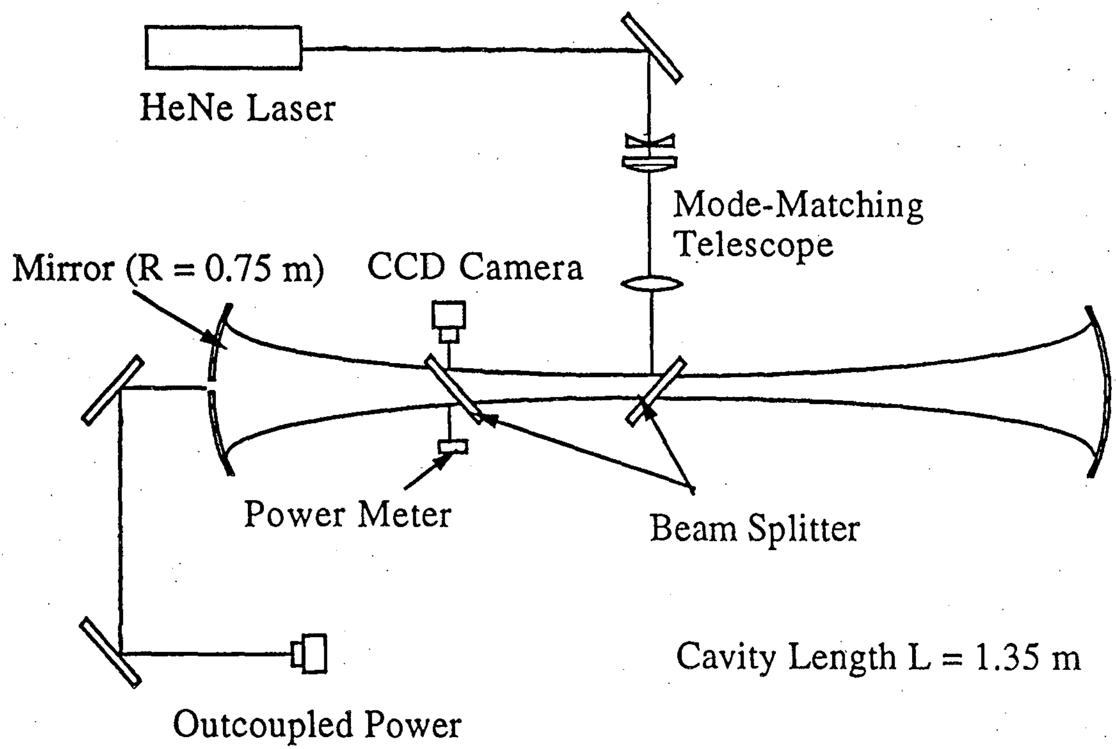
HeNe Laser
Mode-Matching
Telescope
Mirror (R = 0.75 m)
CCD Camera
Power Meter
Beam Splitter
Cavity Length L = 1.35 m
Outcoupled Power

Figure 1

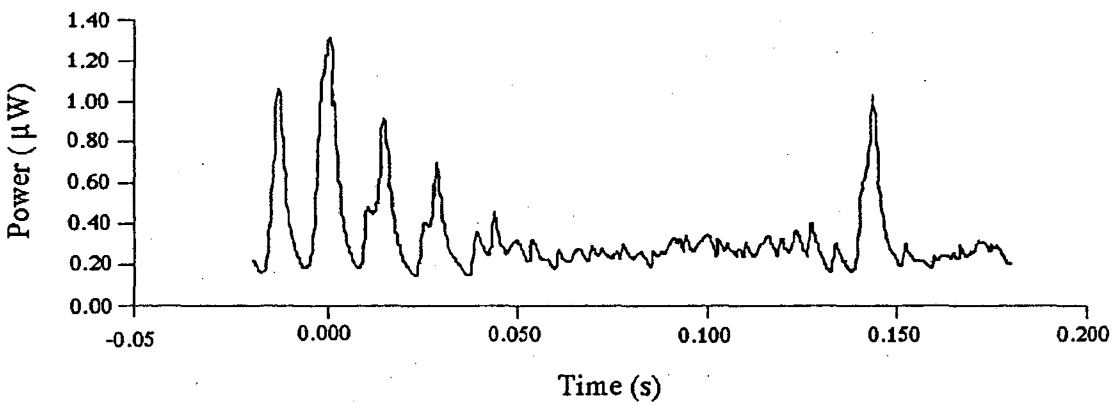
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Power (µW)
-0.05
0.000
0.050
0.100
0.150
0.200
Time (s)

Figure 2

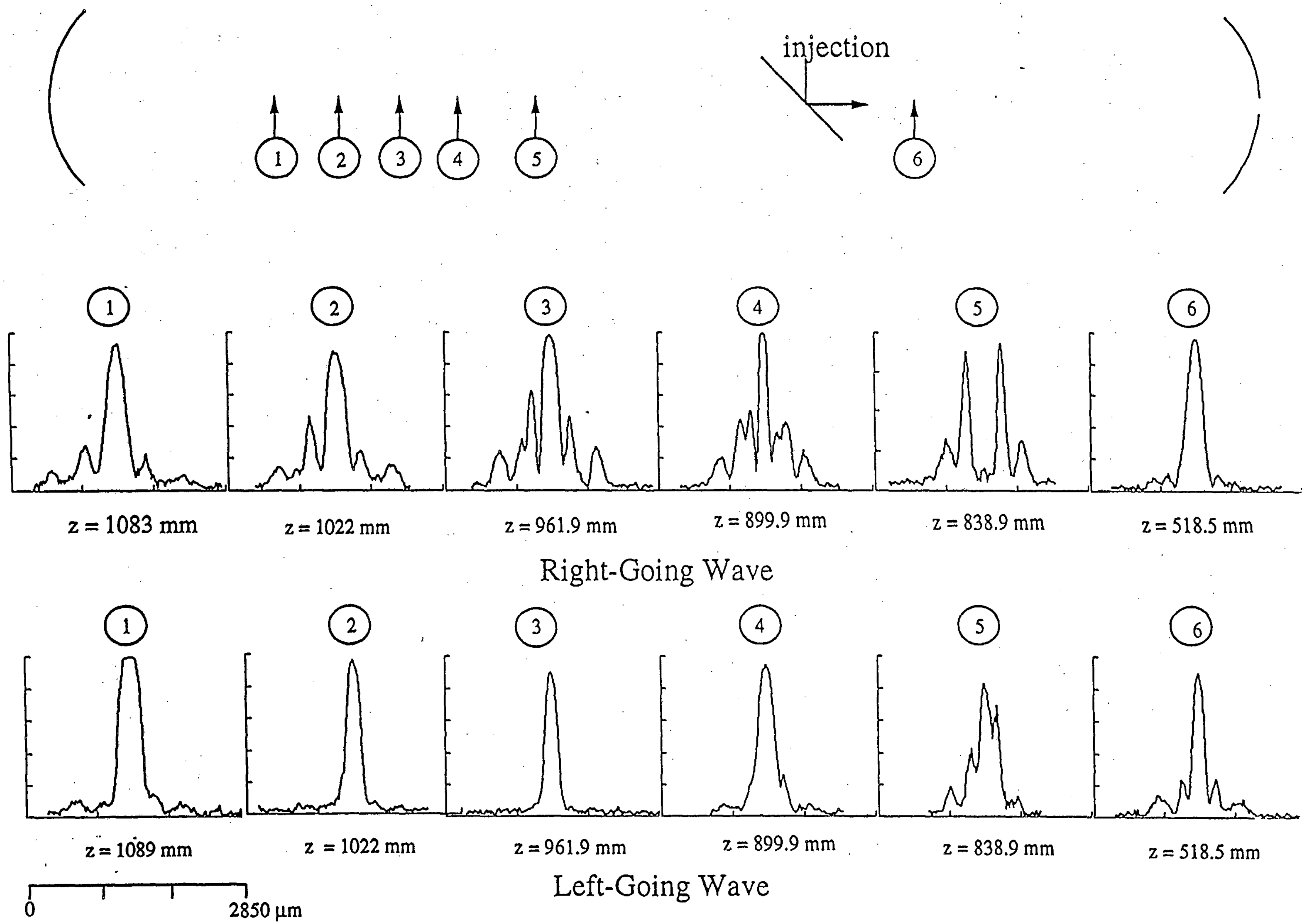
injection
1
2
3
4
5
6
Right-Going Wave
z = 1083 mm
z = 1022 mm
z = 961.9 mm
z = 899.9 mm
z = 838.9 mm
z = 518.5 mm
Left-Going Wave
z = 1089 mm
z = 1022 mm
z = 961.9 mm
z = 899.9 mm
z = 838.9 mm
z = 518.5 mm
0
2850 µm

Figure 3

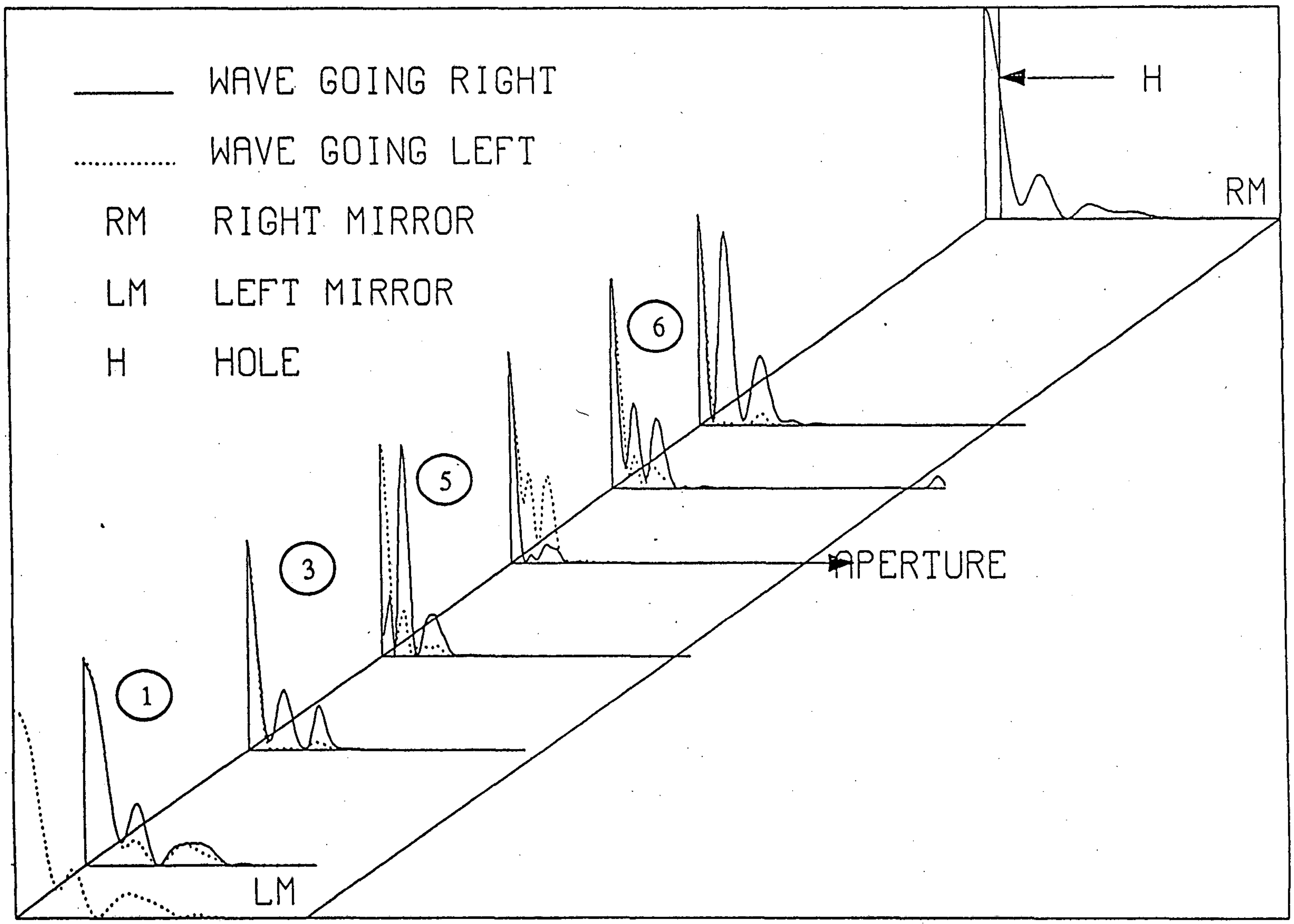
WAVE GOING RIGHT
WAVE GOING LEFT
RM RIGHT MIRROR
LM LEFT MIRROR
H HOLE
H
RM
6
5
3
1
APERTURE
LM

Figure 4

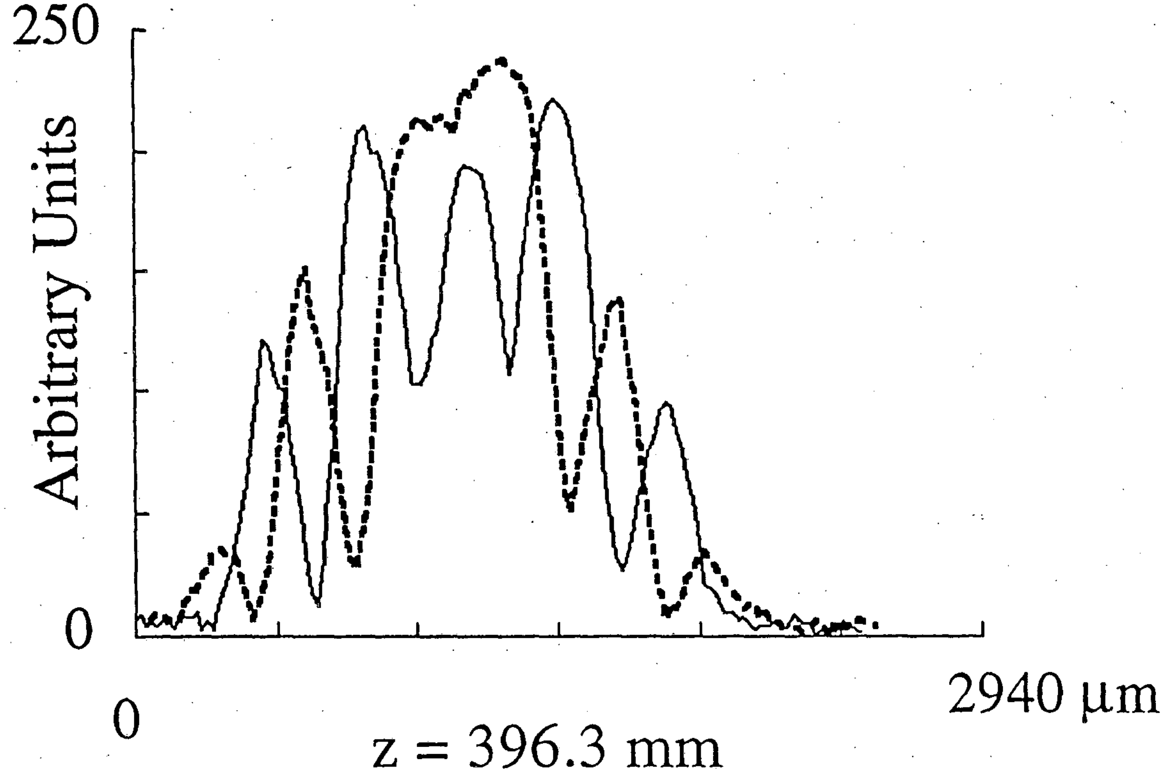

Figure 5

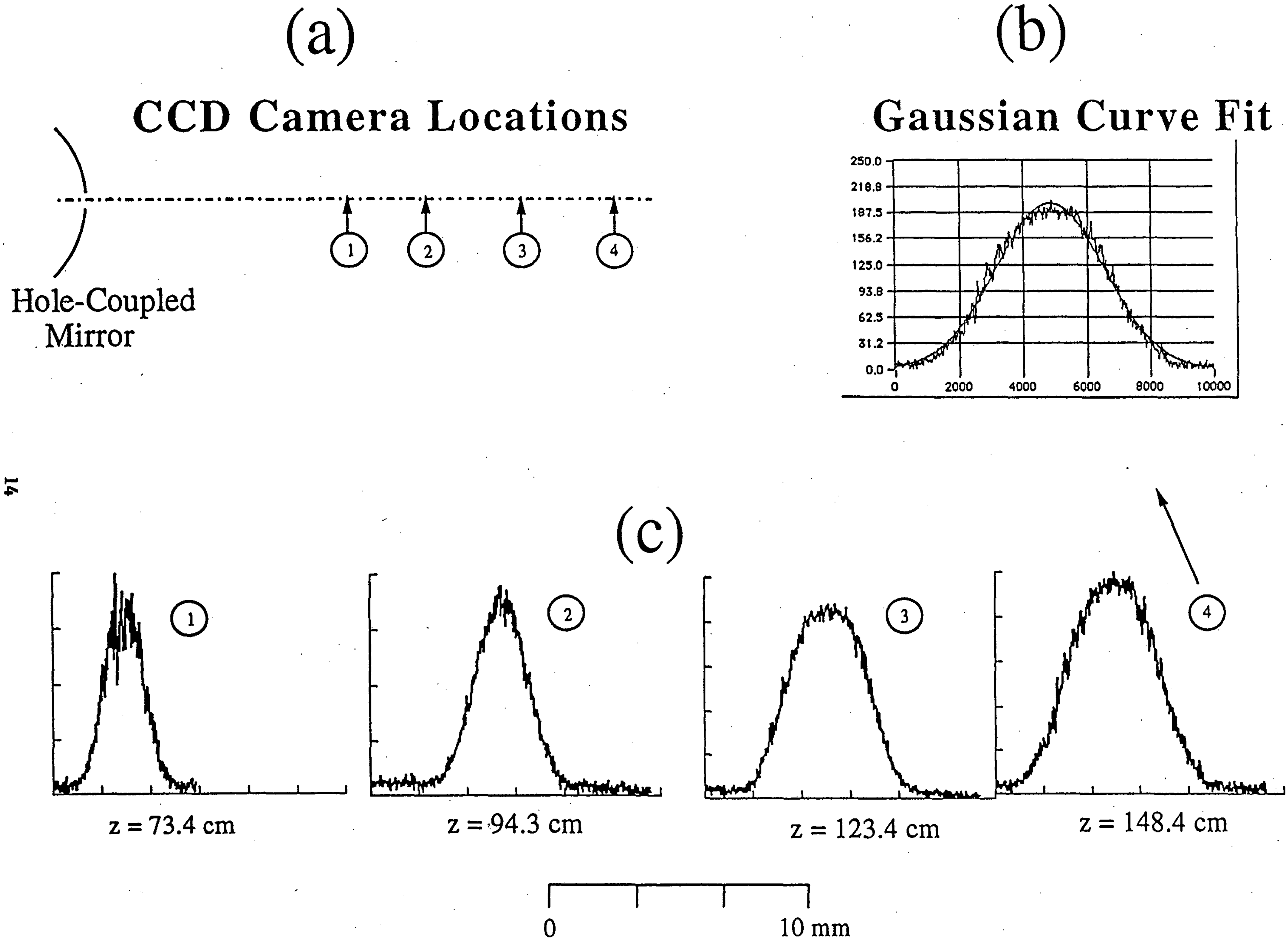
(a)
CCD Camera Locations
Hole-Coupled Mirror
1
2
3
4
(b)
Gaussian Curve Fit
250.0
218.8
187.5
156.2
125.0
93.8
62.5
31.2
0.0
0
2000
4000
6000
8000
10000
(c)
1
2
3
4
z = 73.4 cm
z = 94.3 cm
z = 123.4 cm
z = 148.4 cm
0
10 mm

Figure 6

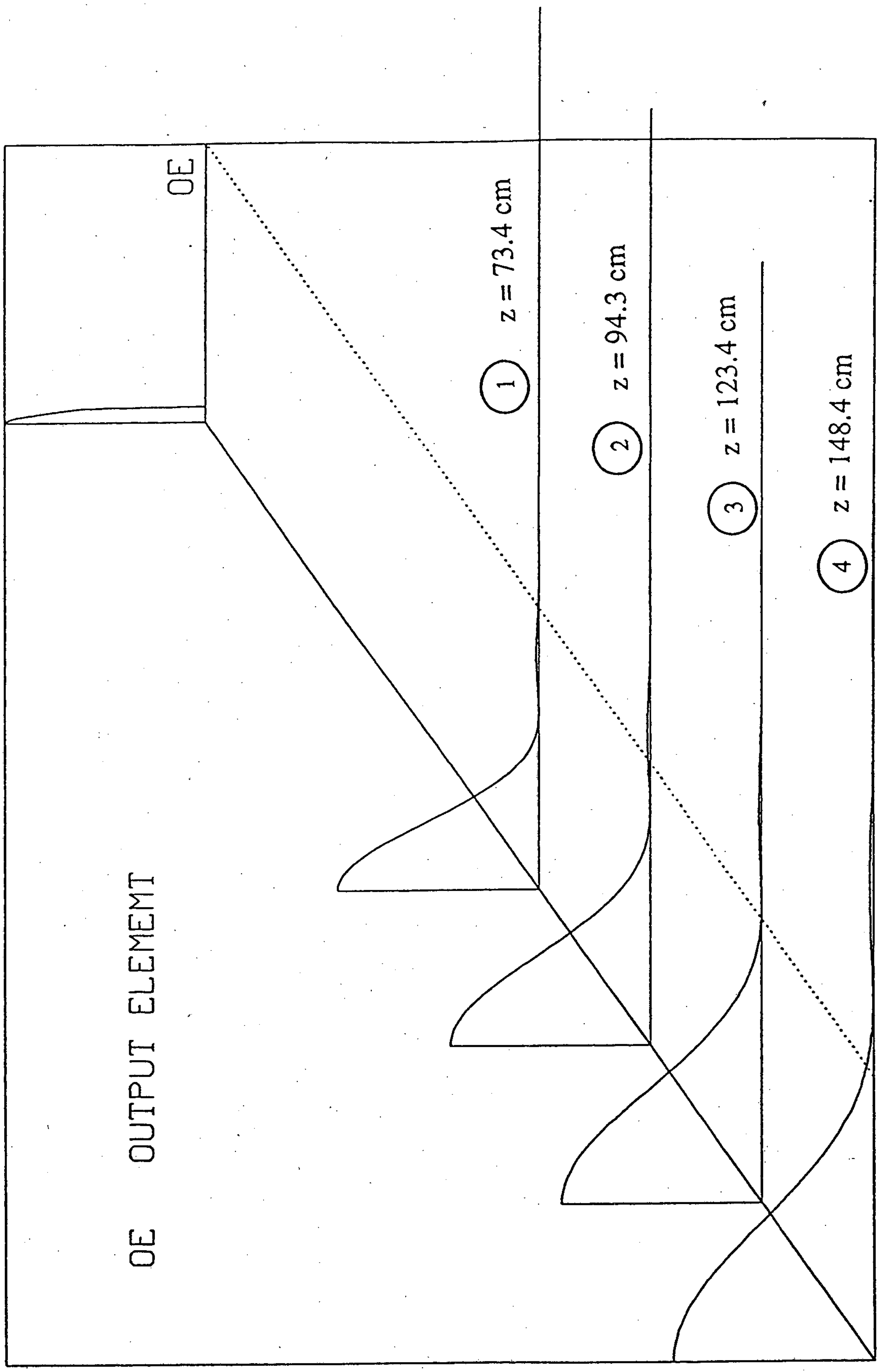

Figure 7

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