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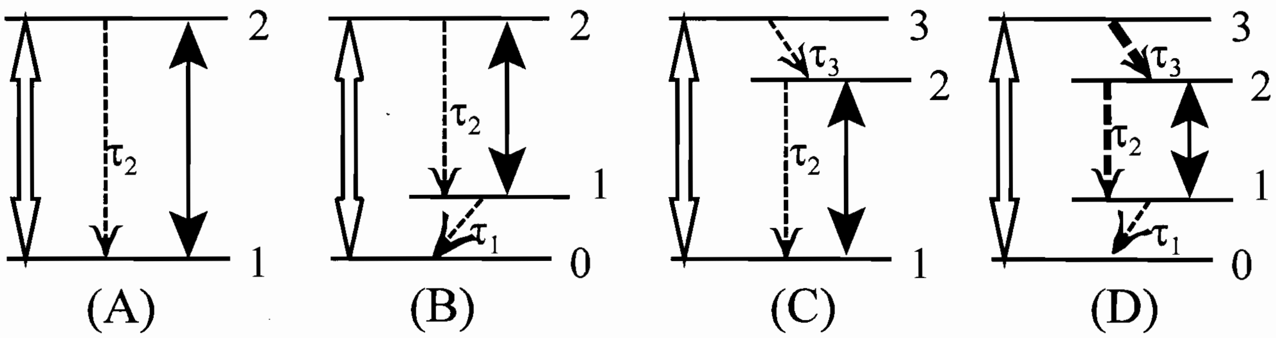
Instructions: Complete each of the following problems. Turn in this exam plus any attachments.

(1) **Lasers.** Consider the four laser systems below. The hollow double-headed arrows represent optical pumping (always between the lowest and highest state), dashed lines indicate the relaxation routes by incoherent processes, and solid-double arrows represent stimulated emission and absorption by laser radiation (always between states 2 and 1). The point of this problem is to rank the four cases shown from worst to best and to justify your ranking. Each system is closed, that is all the population is in one of the listed states. For simplicity, assume that all the energy levels are non-degenerate states and that decay processes only couple to the next lowest level (as shown in the figure). The following quantities may be useful for this problem:

N_j — is the population density in the j[th] level [systems in j[th] level/m^3]
P — is the pumping energy density [joules/m^3]
$c{\cdot}P$ — is the pumping irradiance [watts/m^2]
I — is the laser transition irradiance [watts/m^2]
σ_{ij} — is the absorption cross section between state i and j [m^2]
τj — is the decay time of the j[th] state to the j-1 state [sec]
$h\nu/2\sigma\tau$ — dimensionless "saturation intensity"
$\sigma I/h\nu$ — stimulated rate [1/sec]



(A) For each case, write the laser rate equations for the population in each level. Assume optical pumping as shown, and remember to include both absorption and stimulated emission by the pump and the laser light. Why is the rate equation approach an approximate analysis?

(B) Of these systems, only three are viable for use as a cw laser. Which system cannot be used for a laser? Base your answer on the rate equations you derived in part (A). Hint: What is the requirement on the intensity of the pump to achieve optical transparency?

(C) Of the remaining three systems that are theoretically capable of lasing, give a physical example for two of them.

(D) Rank the four cases from worst to best and justify your ranking. Consider how the τ_j's must be related in order to make efficient lasing systems. (Continue on next page ...)

(E) Solve the laser rate equations for case (D). Assume steady state and ignore stimulated emission by the laser field (threshold calculation). Now derive a formula for the pump intensity that is required for optical transparency ($\Delta N = N2\text{-}N2 = 0$) in terms of the pumping power. Consider the limit that τ_1 & $\tau_3 \to 0$ and $1/\tau_2 \to 0$. What will the power efficiency of this laser be?

(2) **Geometrical Optics I.** An optical system consists of two thin lenses plus a stop and has the following $y - \bar{y}$ diagram. The tics in this diagram are one unit and the optical invariant is one unit.

(A) Identify on the $y - \bar{y}$ diagram the location (i.e., coordinates) of the principal planes.

(B) Identify the location of the aperture stop and the entrance and exit pupils.

(C) What are the diameters of the aperture stop and the entrance and exit pupils?

(D) Where is the object located?

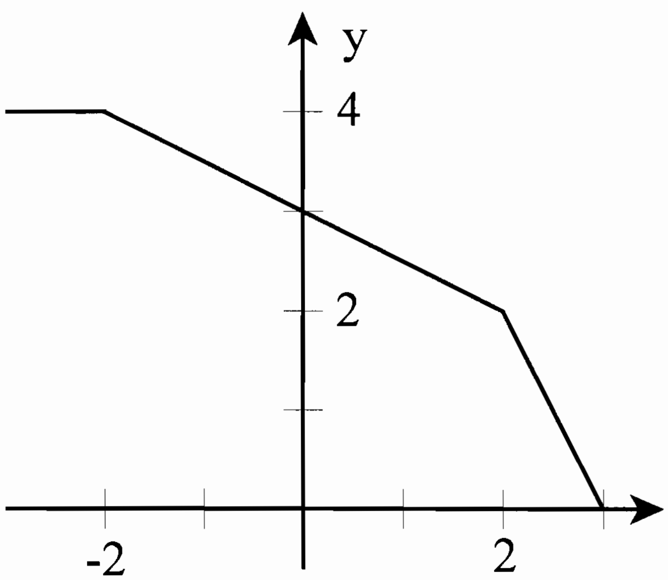
(E) What is the transverse magnification of the system?

(F) What is the focal length of the system?

(G) What are the focal lengths of the two lenses?

(H) What is their separation?

(I) How far is the image away from the second lens?



(J) What is the distance from the first/second lens to the front/rear principal plane?

(K) What are the minimum diameters of the two lenses so there will be no vignetting?

(L) Where should the stop of the system be shifted to make the system telocentric in image space?

(M) Draw the stop-shifted $y - \bar{y}$ diagram that is telocentric in image space.

(3) **Geometrical Optics II.** On Page 4 there is a diagram of a simple optical system composed of two thin lenses and an aperture stop. The lenses are identical having a focal length of 40mm and are 40mm apart. We place a 25mm high object 40mm in front of the first lens. The aperture stop diameter is 30mm.

(A) Use the ray chart and trace conditional A-ray and B-ray through the system (as given, *i.e.*, y_{A0}=0mm & nu_{A0}, *and* y_{B0}=25mm & nu_{B0}=0). Find the image location.

(B) Find the Chief and Marginal Rays and trace them through the system. Draw them on the figure (which is to scale).

(C) On the figure locate and label: the image, the chief ray, the marginal ray, the principal planes, the focal points, the exit pupil and the entrance pupil. Supply the data requested on page 4.

Surface #	Object	1	2-stop	3	4-Image
$-\Phi_j$	0		0		0
t_j/n_j	40mm	20mm	20mm		
y_A	0mm				
nu_A	1				
y_B	25mm				
nu_B	0				
Marginal Ray					
y	0		15mm		
nu					
Chief Ray					
$\bar{y}$	25mm		0		
$\bar{n}\bar{u}$					

If Additional space is needed to explain what you are doing please show this work on a separate 8½"x11" sheet of paper. Make a note here that such a sheet is attached.

Front Principal Plane: $L_{\#1} \rightarrow P_1 =$

Rear Principal Plane; $P_2 \rightarrow L_{\#2} =$

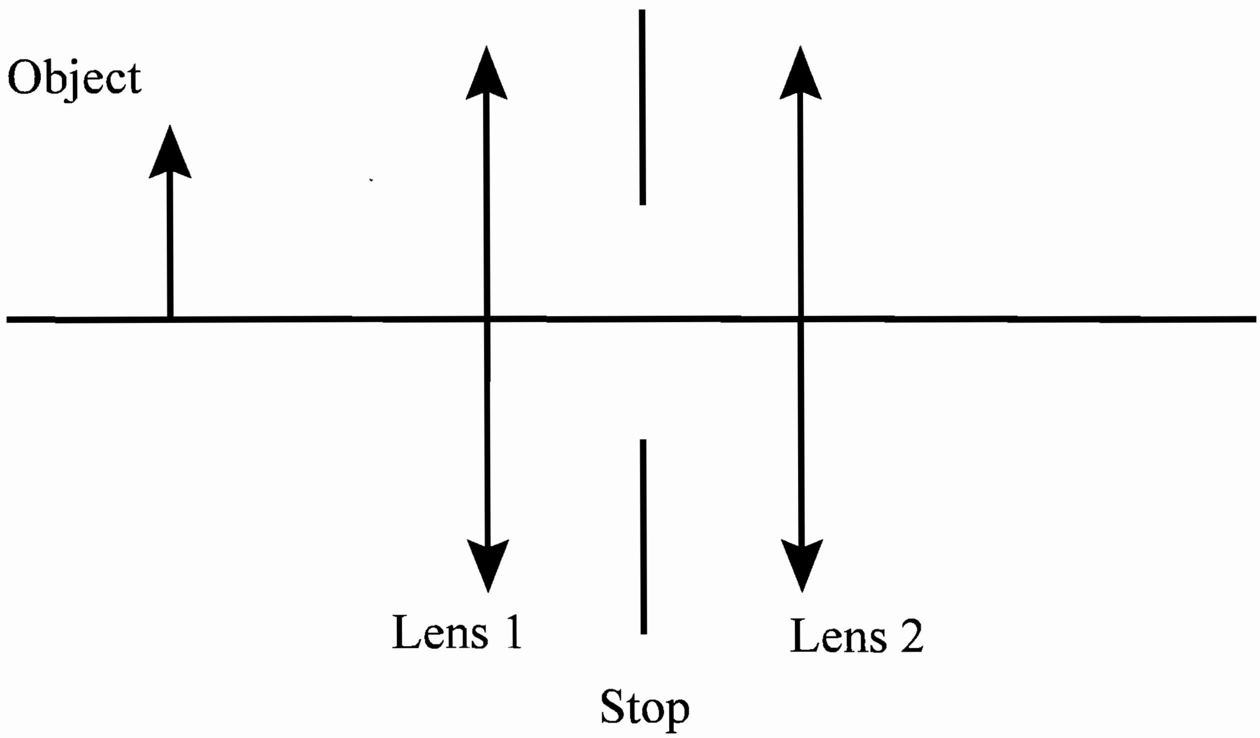
Entrance Pupil: $L_{\#1} \rightarrow E_1 =$

Diam of $E_1 =$

Exit Pupil: $E_2 \rightarrow L_{\#2} =$

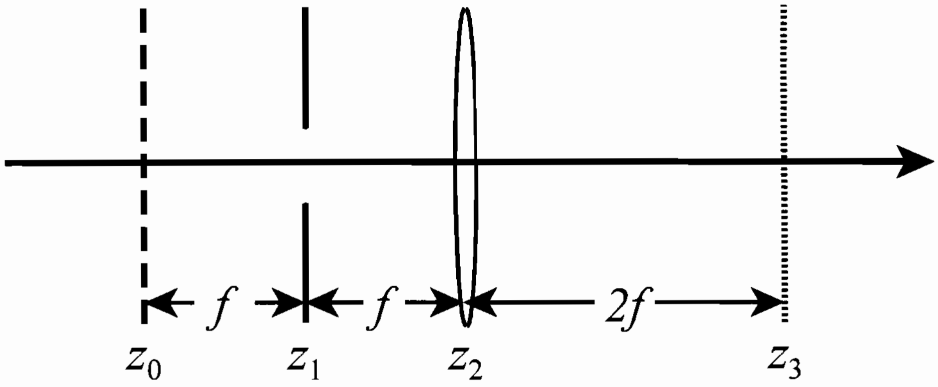
Diam of $E_2 =$

System's Focal Length $f =$



(4) **Radiometry.** In the optics lab there is a blackbody source with a 2 cm diameter aperture exit pupil. There is also a 50 mm focal length lens with a 2 cm diameter clear aperture. You mount the lens 25 cm in front of the BB exit window. The temperature of the BB is 2000°C. You then move a detector along the optical axis, starting at the lens and moving back to the far wall of the lab. Plot the expected irradiance on the detector. Assume no losses and an ideal detector that detects all radiation. Label important points (distances) and give values of the irradiance. (Hint: You will need to find the location of the image and its size. The lens will be the exit pupil. Why? Also, note Stefan-Boltzmann constant: σ_{SB} = 5.67E-12 watts/cm^2 °K^4.)

(5) **Physical Optics.** Consider the optical system shown in the figure below.



The object plane is at z_0, the system stop is at plane z_1, the lens is at plane z_2, and the observation plane is at z_3. The distance between z_0 and z_1 is $z_{10}=f$, between z_1 and z_2 is $z_{21}=f$, and between z_2 and z_3 is $z_{32}=2f$. The focal length of the lens is f. The source is a point source with wavelength λ on the optical axis, and therefore we write the field distribution in the z_0 plane as

$$u_0(x,y) = A\,\delta(x,y)$$

The stop is a rectangular opening of width a and height b, thus its transmission function is

$$t_1(x,y) = rect\left(\frac{x}{a},\frac{y}{b}\right)$$

The lens diameter is sufficiently large as to pass all the light incident upon it.

(A) Find the field just before the aperture stop, $u_1^-(x,y)$.

(B) Find the field just after the aperture stop, $u_1^+(x,y)$.

(C) Find the field just before the lens, $u_2^-(x,y)$.

(D) Find the field just after the lens, $u_2^+(x,y)$.

(E) Find the field and irradiance distribution in the observation plane, $u_3(x,y)$.

(F) How do the results of (A)-(E) change if the point source is translated in the y-direction by an amount y_0, so that $u_0(x,y) = A\,\delta(x,y-y_0)$?