Physics In Modern Medicine

Fall 2009

Take-home Midterm Exam

Name________________________

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Assigned: Friday, October 9, 2009 in class and in electronic format in email.
Due in electronic format: Wednesday, October 14, 2009, by Noon, EST. (This of course means that it should be in my inbox by 6am Hawaii Standard Time!)

Late exams will be penalized **10 points/half day.**

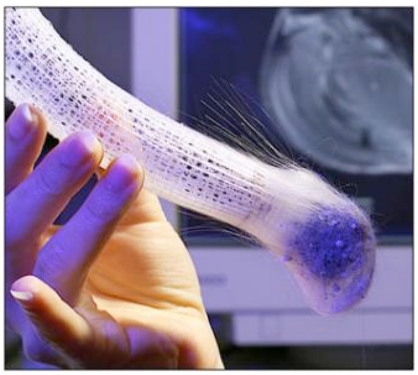
Ground rules: The total credit for the exam is 140 points with each subpart worth 7 points and there are 20 subparts. Be sure to start by reading all the questions carefully so you understand what you are being asked to do, and answer all parts. Explain your reasoning and show all of your work--don't simply write down numerical answers for the mathematical parts. This is crucial--failure to explain answers or show your reasoning will result in my inability to give you full credit, especially if you only write down a wrong numerical answer. Pay attention to the appropriate units, prefixes and powers of ten for full credit. You **must include units** for physical quantities. Even if you aren't sure about how to completely answer each part, put down as much work as you can, as clearly as possible, for partial credit. I will give partial credit for *everything relevant and correct* you have written down!

The exam is open book and open notes. You may only consult the textbooks by Kane and Wolbarst as well as any class notes or the class lecture slides. You may not communicate in any way with any other person during the exam, and you may not consult the web except for problem #8, which lists a web address. For those of you that know my exam style, doing so would be pointless anyway. You may, of course, use a calculator during the exam.

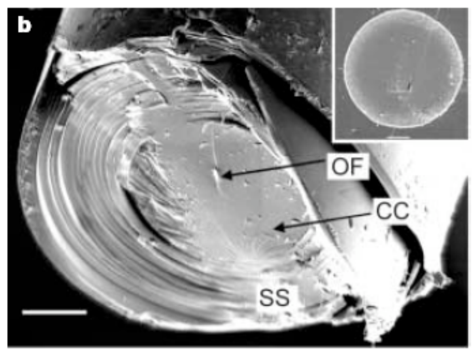
I will do my best to answer any questions that you may have up until Monday afternoon until about 11pm EST (my plane lands at 4:30 in Hawaii.) After Monday night, I will 6 hours behind you in time, so there may be a delay in the response. Be patient, if I'm able, I will respond as soon as I can.

1. Fiber optics

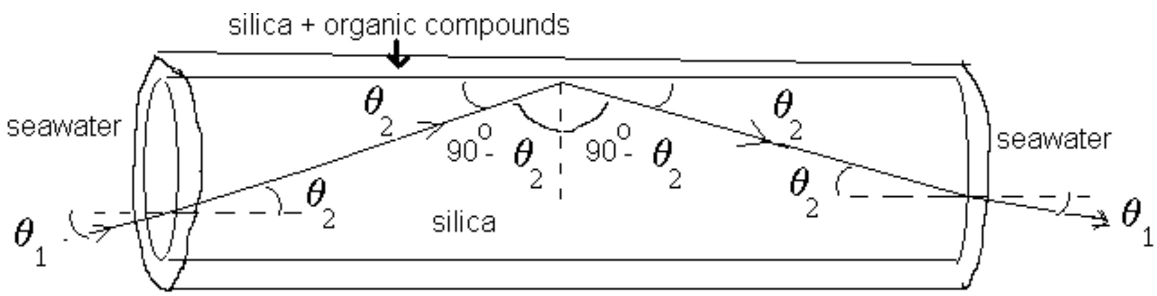
Sea sponges in the family Euplectella (Venus Flower Basket) have at their base long needle-like structures called spicules, made of a combination of the mineral silica and organic compounds. Scientists have investigated whether these spicules can act as optical fibers. Each spicule consist of an inner cylindrical core made of the mineral silica, surrounded by an outer cladding-like coating made of a mixture of silica and organic compounds. All this is illustrated in the images (A) through (C) below. In figure (C), SS is the outer coating while CC is the center core. The tough, flexible outer coating allows the spicules to bend into very small angles without cracking, unlike current optical fibers, so scientists are investigating whether they can help in designing more flexible optical fibers for medicine.



(A)



(B)



(C)

(A) Photo of the sea sponge Euplectella. The fiber optic-like spicules are glass-like fibers projecting from the base.

(B) Cross-sectional image showing the central silica core and outer coating. (Joanna Aizenberg/Lucent Laboratories)

(C) Cartoon representation of a ray of light entering one end of the spicule's silica center core, reflecting from the interface with the outer coating and exiting the other end. (The angles shown are not necessarily realistic for these values of index of refraction.)

Here is some useful information about the optical properties of this system:

Medium	**Index of refraction**
Seawater	1.34
Silica (inner core of spicule)	1.46
Silica + organic compounds (outer layer of spicule)	1.43

a. Explain why a spicule can act as an optical fiber. Compute what its critical angle for total internal reflection would be. Explain your reasoning and show your calculations!

b. Would the spicules still work as an optical fiber if they did not have the outer layer of silica and organic compounds? (That is, if they consisted only of a fiber of pure silica surrounded by seawater along its entire length.) Explain your reasoning.

c. Derive a value for the angle θ_2 using your calculation for the critical angle for total internal reflection from part (a) (just choose a value if you could not compute it), then compute the angle, θ_1, at which light *exits* the spicule. Use a drawing to explain clearly why your value for θ_1 is also the largest angle that can **enter** the spicule and still undergo total internal reflection. (Hint: you should show in your sketch the range of angles for light rays that will undergo total internal reflection.)

2. Laser surgery

A new titanium:sapphire laser has recently (September 2008) been approved for ophthalmological applications. In particular it provides a new treatment for glaucoma, a condition where a buildup of excess pressure in the eyeball can eventually damage the optic nerve. The procedure called *laser trabeculoplasty* relieves this pressure by creating a new drainage network of laser-induced holes in the eye's natural drainage structure, called the *trabecular meshwork*. Previously, argon ion lasers were one of the main lasers used for this procedure. Here are some typical specifications for each laser being considered. Use this information in answering the questions below.

Laser type	**Argon ion**	**Titanium:sapphire**
Wavelength	488 nm	790 nm
Type of laser	CW	Pulsed
	power = 1 watt	Energy / pulse = 30mJ
Pulse repetition rate	Continuous Wave	1 Hz
Pulse width	Continuous Wave	8.0 μs
Spot Diameter	100 microns	200 microns

a. What part of the spectrum does each laser's wavelength belong to? What is the energy per photon for each laser in eV and in Joules? What are the frequencies of each photon? Is either laser able to break chemical bonds through absorption of individual photons?

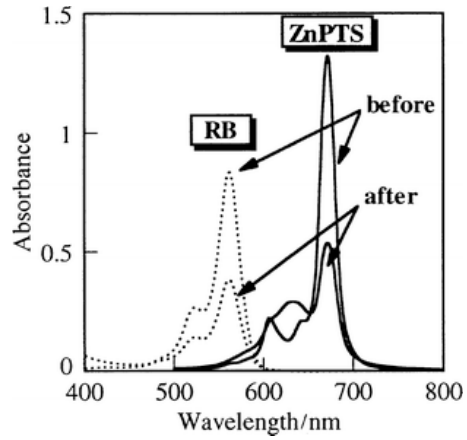
b. Calculate the instantaneous and average *power* for each laser. What is each laser's average and instantaneous *power density*? (Answer using standard units for laser surgery in each case.)

c. The newly approved laser uses *single* pulses to achieve its effects—that is, only a single pulse is used to create each drainage hole. Assume the argon ion laser employs a 1 second exposure time to create each hole. What is the energy used to create a hole in each procedure?

d. Given the above information, what advantages would you expect the new titanium-sapphire laser to offer compared to the argon ion laser because of its different wavelength of operation—and why? (You may find it useful to know that the main pigment in the *trabecular meshwork* is melanin.)

3. Photodynamic therapy

Scientists and physicians are constantly working to identify new photosensitizers for photodynamic therapy (PDT) for ophthalmology, dermatology, cancer chemotherapy and other applications. Below we see an absorption spectrum for chemical compounds that are two new candidates for cancer therapy using PDT. We will call these two compounds just RB and ZnPTS. Reference this plot in answering the following questions. (The "before" curves correspond to absorption of each compound before laser light has been applied, while the "after" curves correspond to their absorption after each has been exposed to laser light.



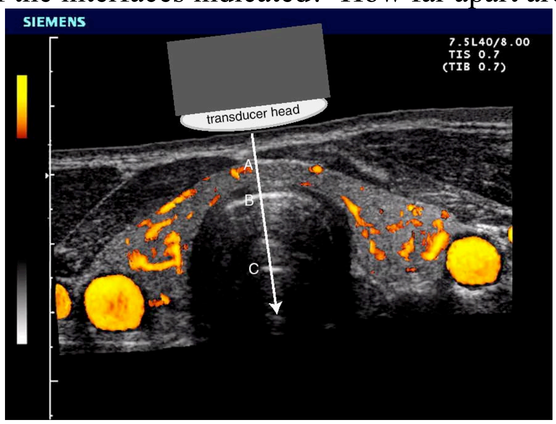
a. What laser(s) would be the best match(es) (if any!) to use in performing PDT on using these two photosensitizers? Include any and all lasers that would be good matches. Be sure to provide both an answer and your reasoning, for each compound. Would either of these photosensitizers be good possibilities for PDT in treating tumors? Explain any assumptions that you make in answering this part. (You may assume that is it possible to decrease the power output of any laser if necessary by using special filters.)

b. What else would you need to know about these two compounds to determine whether they would be effective photosensitizers? Be complete in your answer.

4. Ultrasound Imaging

Consider the ultrasound scan shown below in answering the following questions. Assume the transducer is located at the top of the image, as shown with the figure. You do not need to know anything about the anatomy being portrayed here to answer these questions.

a. An ultrasound imaging device measures the following three times for echoes to return to the transducer in an imaging scan from the interfaces indicated: A: 1.5×10^{-5} seconds, B: 2.9×10^{-5} seconds and C: 5.2×10^{-5} seconds. How far below the transducer are each of the interfaces indicated? How far apart are interfaces B and C?

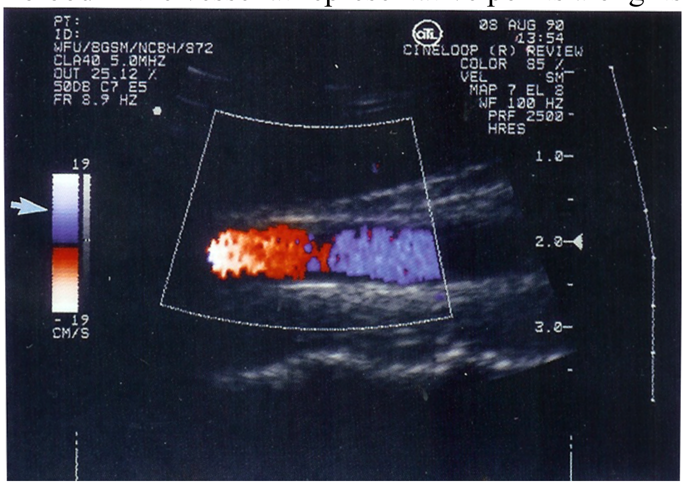


b. What would the A-mode intensity display (as a function of distance) along the white arrow look like? You will need to make a plot and assume an incident intensity of 1 W/m^2. What can you tell about the variation of acoustic impedance along this direction from your plot?

c. Assume this image was made with a 7.5 MHz transducer. Describe qualitatively at least two ways the image might change (and why) if it had instead been made with a transducer with a frequency of 3.5 MHz or 15 MHz.

5. Doppler Ultrasound

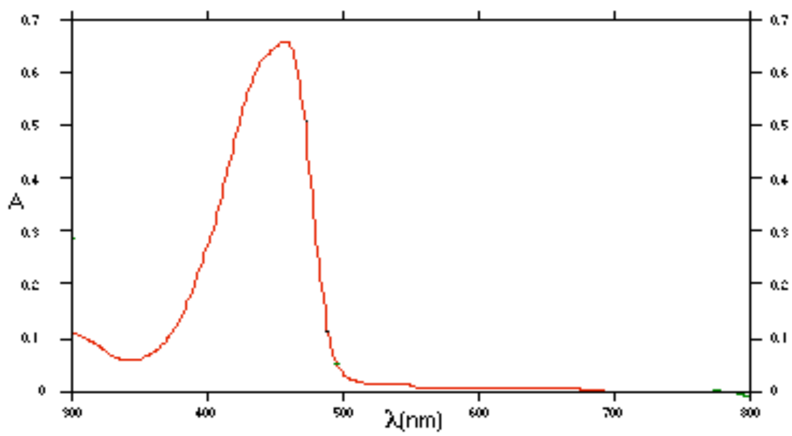
The following image is a color flow Doppler ultrasound image described as flow in a straight line along a blood vessel. The source states, of the color map used: "In this map, blue and red are assigned to positive and negative Doppler shifts, respectively, progressing to white at the extremes." (That is, for the largest values of flow speed.) Explain how this color flow image could result from flow in a straight line along a blood vessel in this measurement geometry. Use a sketch, indicating the direction you have assumed for the pathway of the ultrasound beam at various times in the scan and the direction of flow of blood in the vessel at representative points along its length.



6. Phototherapy—More absorption of light

A light from a lamp is used to treat jaundice, or the condition that results when too much *bilirubin* is present in newborn babies. The absorption spectrum of *bilirubin* is shown below. The quantity A plotted along the y-axis is proportional to the Absorption at each wavelength, λ.

a. Explain what color of light you would expect to use for phototherapy for jaundice and JUSTIFY YOUR ANSWER FULLY based on the absorption spectrum. Just stating a color or colors isn't enough—to get credit you need to explain why this is determined by the absorption spectrum!



b. Imagine you are an FDA investigator looking into a firm that has begun to market light emitting diodes (LED's) for photodynamic therapy of various kinds. Explain why you would or would not consider the following system an appropriate choice for phototherapy for jaundice, based on an evaluation of each of their claims as follows: "Our Bili-LED system has a peak emitted wavelength between 450 and 475 nm. Our unit has the advantage that it offers high intensity light with little emission in the ultraviolet and infrared compared to conventional lamp sources for jaundice therapy on the market."

7. Lasers in medicine

In *laser lithotripsy*, extremely high power densities are used to disrupt kidney stones and other painful mineralized deposits. High power pulsed holmium-YAG laser systems can be used in this application.

a. A laser used for lithotripsy is transmitted into the kidneys laparoscopically using an optical fiber. When laser light exits the optical fiber, the intense laser beam instantly vaporizes the water at the very tip of the optical fiber, creating a shock wave that destroys the stone. (No focusing of the laser is needed for the high instantaneous intensities used.) To achieve this result, power densities of 10^{10} watts/cm^2 are required. Use as your effective laser spot size the diameter of the optical fiber, 1000 microns. What must the instantaneous laser power be in order to achieve the necessary power density required to generate the shock waves needed to break up kidney stones?

b. Each pulse lasts 1.0ns long and the optical fiber can carry up to 100mJ without melting. How much energy is emitted per pulse? Will it melt the optical fiber?

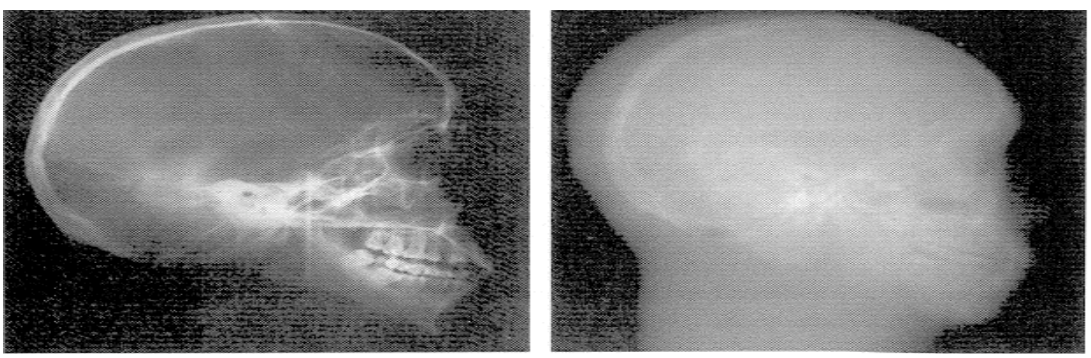
c. One source lists a fluence of 100 J/cm^2 for this technique. How long must the laser be turned on in order to achieve this value if the pulse repetition rate is 20 Hz?

8. X-ray imaging

Suppose that you want to use copper x-rays for imaging. You wouldn't really want to use Cu x-rays since x-rays below 10keV do not penetrate far into the body. Copper x-rays have a wavelength of $1.54x10^{-10}m$ and a density $\rho = 8.92\ g/cm^3$.

a. What is the *HVL* for the copper x-rays and if the beam has an intensity of $1\ W/m^2$ incident in a material, what percent of the x-rays are transmitted? You will need the attenuation coefficient for Cu x-rays, which can be found at http://physics.nist.gov/PhysRefData/XrayMassCoef/ElemTab/z29.html. (Hint: The mass attenuation coefficients are energy dependent.)

b. The following radiography images were made with x-ray sources, not necessarily Cu (and probably not copper), of different average energies. Which image was made with the higher and which with the lower x-ray energy? Explain your reasoning.



These questions are not for credit and do not have to be turned in with the exam. I will be looking for answers to these questions when I return. Please type your answers below and print them out then give them to me when class resumes. These can be anonymous if you prefer, or you may put your name on them if you'd like.

1. What is your impression of the course so far?

2. What are the topics that you like/dislike and why?

3. What could be done to improve the quality of the remainder of the course?

4. Are there any questions, comments or complaints that you would like me to address?