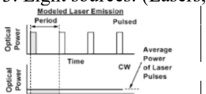
EE 6301

Week1 Introduction

1.

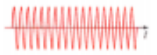
Week2 Optical Biosensor

1. Structure of Biosensor:
Light source -> sensor -> light analyzer
2. Key Parameters of Biosensors:
Specificity: what is the analyte being measured
Sensitivity: the quantity (or concentration) of the analyte (LOD) (=slope)
Detection limit / Limit of detection (LOD)
$LOD = 3 \times s / m$
3. Light sources: (Lasers, LED, lamps)



s: standard deviation;
m: slope;
ceil
CW: continuous wave

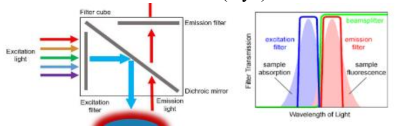
4. General requirements on sources:
Spatial coherence
Low noise (RIN)



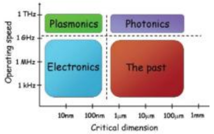
Adequate power output (SNR)
5. Light as Waves - The EM Wave Model:
$E(z,t) = E_0 cos(\omega t - kz)$
angular frequency: $\omega = 2\pi\nu$
wavelength: $\lambda = c/\nu$
wave vector: $k = 2\pi/\lambda$
speed of light: $c = 3 \times 10^8$ m/s
6. Light as Particles – The Particle Model
Energy is delivered in photons (光子).
Energy of one photon: $E = h\nu = 1239.8/\lambda[nm]$
Planck's constant: $h = 6.63 \times 10^{-34}$ Joule·s
$1W = 1J/s$ $1\,eV = 1.602 \times 10^{-19}$ J
Photon momentum (动量): $p = h/\lambda$
7. Refractive Index
$n = Speed\,in\,Vacuum / Speed\,in\,medium$
Snell's Law: $n_1 sin(\theta_1) = n_2 sin(\theta_2)$
Total internal Reflection: $\theta_c = \sin^{-1}(n_2/n_1)$
8. Evanescent Wave Field
Penetration depth: $d = \lambda_0 / 4\pi\sqrt{n_1^2 \sin^2\theta_1 - n_2^2}$
(assuming incident angle = 90°)
Ligh intensity: $I(d) = exp(-d/L_0)$
9. Light-matter Interactions
Incident = Reflected + Transmitted + Absorbed
Absorption / A+Luminescence / Scattering
10. Absorption spectroscopy
Absorbance: $A = \varepsilon cL = -\log_{10}(I/I_0)$
$I(\lambda) = I_0(\lambda) \cdot e^{-\varepsilon'(\lambda)CL}$, $\varepsilon = \varepsilon'/2.303$
ε: molar absorption coefficient ($M^{-1}cm^{-1}$)
c: molar concentration (M)
L: optical path length (cm)
11. Fluorescence Lifetime & Quantum Yield:
$\Phi = N_{emit}/N_{absorb} = k_r / (k_r + k_{nr}) = k_r\tau_s$
k_r : fluorescence rate constants
12. Scattering (no absorption):
Elastic scattering: no energy change
Inelastic scattering: energy change
Frequency change, Vibration, Raman
13. Raman scattering
stokes: E↓ f↓ ; anti-stokes: E↑ f↑
wavenumber: $\bar{\nu} = 1/\lambda\ (cm^{-1})$
Raman shift$[cm^{-1}] = \frac{10^7}{\lambda_{ex}[nm]} - \frac{10^7}{\lambda[nm]}$
14. Grating
Dispersion: $d\sin\theta = m \cdot \lambda$
Resolving Power: $R = \lambda/d\lambda = mN$
$\Delta\lambda$: resolution m: diffraction order Ceil(N)

Week3 Optical Biosensor (2)

1. Fluorescence Biosensors-(Dye) Labeled Sensors:

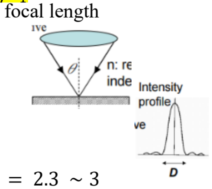


1) Excitation of a fluorophore through the absorption of light energy. 2) A transient excited lifetime with some loss of energy. 3) Return of the fluorophore to its ground state, accompanied by the emission of light.
2. Selecting Filters:
3. Label-Free Sensor Working Principle
Sensitivity: $S_\lambda[nm/RIU] = (\lambda_2 - \lambda_1)/(n_2 - n_1)$
Resonant wavelength: $\lambda = 2\pi r n_{eff}/m$
r: fiber radius n_{eff}: effective refractive index
Full Width at Half Maximum:
FWHM $= x_2 - x_1$
$f(x_1) = f(x_2) = 0.5 f_{max}$
Q-factor: $Q = f_0/\Delta f$ Δf由$0.5 I_{max}$决定
f_0: Resonant/central frequency
Figure of Merit: FOM = Sensitivity/Δf
Surface Plasmon Biosensor:
Materials:
Al/Cu/Ag/Au

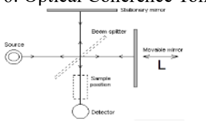


Week4 Biomedical Imaging (1)

1.Light propagation in tissues:
attenuation coefficient: $\mu_t[cm^{-1}] = \mu_a + \mu_s$
μ_a: absorption coefficient μ_s: scattering
μ_a ≡ probability of absorption / unit pathlength = inverse of the mean-free-path for absorption
light attenuation:
$I(x) = I_0 \cdot e^{-\mu_t L} = I_0 \cdot e^{-(\mu_a + \mu_s)L}$
loss of incident light: dI=absorption+scattering
2. Fresnel reflection coefficients (normal incident):
$R = ((n_1 - n_2)/(n_1 + n_2))^2$, n_1 incident
3. Property of thin lens:
thin lens equation: $(1/S_1) + (1/S_2) = (1/f)$
Magnification: $M = S_2/S_1$
S_1: object distance, f: focal length
4. Diffraction Limit:



Resolution:
$\Delta d = 0.61\lambda_{excited}/NA$
Numerical aperture:
$NA = n_{solution}\sin\theta$
Width of the central band of the Airy disk:
$D = 1.21\lambda/(n\sin\theta)$
In practice: $M\,\Delta d/\Delta x = 2.3 \sim 3$
Δx: the pixel size of the detector
5. Two-photon excited fluorescence
Excited energy= $h\nu_{0.5}$
6. Optical Coherence Tomography (OCT)



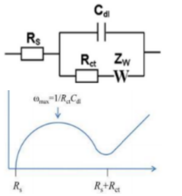
light path difference: 2L
Phase difference: $(2\pi/\lambda) \cdot 2L$
intensity of interference:
$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cdot \cos(4\pi L/\lambda)$

Week5 Optical Bioimaging and Devices

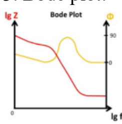
1. Physics of Ultrasound:
$p = p_+ e^{-\alpha x} cos(\omega t - kx)$
angular frequency: $\omega = 2\pi f$
propagation constant: $k = 2\pi/\lambda$
α: attenuation coefficient
Attenuation $= \alpha\left(dB/(MHz\,cm)\right) \cdot l[cm] \cdot f[MHz]$
l 是往返总路程
intensity of the acoustic wave: $I(t) = p^2(t)/Z$
$[W/m^2]$ $p(t)$: pressure, Z: impedance
2. Confusion Matrix
Sensitivity = TP / TP+FN
Specificity = TN / FP+TN
Data on slanted line are large -> good model
Receiver Operator Characteristic (ROC)
Area Under Curve = 1 -> perfect

Week6 Electrochemical Biosensor

1. Electrochemical Calculation
Coulomb Calculation Formula: $Q = I \times t$
Q: Coulombs(C); I: Current (A, amps); t: time(s)
Faraday Constant Formula:
1 mol of electrons = 1F = 96485 C/mol
Avogadro's Num: $N_A \approx 6.02 \times 10^{23} particles/mol$
Moles of electrons: $n_e[mol] = Q/F$
Moles of element: $n_{element}[mol] = n_e/n$
n: electrochemical equivalent
Mass: $m_{element} = n_{element} \cdot M_{element} = \rho \cdot V$
$M_{element}$: Molar mass of silver
2. Randle equivalent circuit:



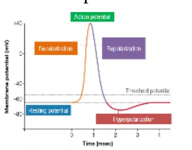
R_s: active electrolyte resistance
R_{ct}: charge transfer R
C_{dl}: double-layer capacity
Z_w: faradaic reaction Z
x-axis: resistance (real part)
y: reactance (imaginary)
origin: $\omega \to \infty$
$Z_{C_{dl}} = 1/j\omega C_{dl}$
$Z_w = (1\text{-}j)\sigma/\sqrt{\omega}$
3. Bode plot:



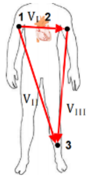
x-axis: logarithmic scale of the frequency
y-axis: logarithm of the impedance Z & phase shift Φ
$\omega = 2\pi f$

Week12 Bioelectricity and Biopotential

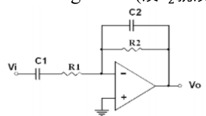
1. Ionic concentrations and channels
Current: $I_K = g_K(V_m - E_K)$
$V_m = V_{in} - V_{out} < 0$
$E_K = ((RT)/(zF)) \cdot \ln([K^+]_{out}/[K^+]_{in})$
g_K: conductance,电阻的倒数
E_K: Equilibrium potential for potassium
R: Universal gas constant (J/(mol·K));
T: Temperature (K) z: 离子电荷数(K+->+1)
F: Faraday's constant
$[K^+]_{out}$: Concentration of K^+outside the cell
2. five steps on the cell membrane:

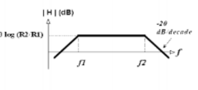


Time(ms)
Membrance potential (mV)
Resting potential
Depolarization
Action potential
Repolarization
Hyperpolarization
Threshold potential
3. Biopotential at Tissue Level:
EEG (Brain)
EMG (Muscles)
$V_d = V_1 - V_2$
ECG (Heart)
$V_I = V_2 - V_1$ (lead I)
$V_{II} = V_3 - V_1$ (lead II)
$V_{III} = V_3 - V_2$ (lead III)



4. The supplementary information:
R: $V = IR$, $Z = R$
L: $V = j\omega LI$, $Z = j\omega L$, $X_L = \omega L$
C: $V = I/j\omega C$, $Z = 1/j\omega C$, $X_c = 1/\omega C$
$Z(\omega) = |Z|e^{j\phi} = |Z|(\cos\phi + j\sin\phi)$
$Z(\omega) = Z' + jZ''$, $|Z| = \sqrt{(Z')^2 + (Z'')^2}$
$V_{A-B} = V_B - V_A$
5. Analog Filter (没C_2就没方框内的项)



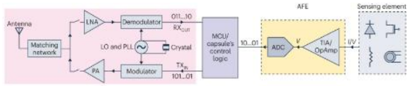


$H(s) = \frac{-V_o}{V_i} = \frac{-sC_1R_2}{(1+sC_1R_1)\boxed{(1+sC_2R_2)}}$, $s = j\omega$

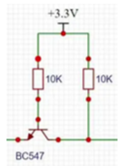
$H(jf) = H_o\frac{j(f/f_1)}{[1+j(f/f_1)]\boxed{[1+j(f/f_2)]}}$, $H_o = -\frac{R_2}{R_1}$
$f_1 = \frac{1}{2\pi R_1C_1}$ $f_2 = \frac{1}{2\pi R_2C_2}$

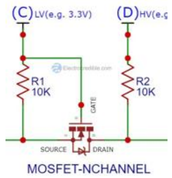
Week8

1. Wireless Sensing System



RF: Antenna, Matching Network, LNA (Low Noise Amplifier), Demodulator, LO and PLL (Local Oscillator & Phase-Locked Loop), Crystal, PA (Power Amplifier), Modulator
MCU (microcontroller) / Capsule's Control Logic
AFE (Analog Front-End): ADC (Analog-to-Digital Converter), TIA / OpAmp (Transimpedance Amplifier / Operational Amplifier)
Sensing Element
2. ADC sampling:
ADC resolution: $\Delta V_{LSB} = V_{min\_peak}/2^n$ (n-bit)
Minimum sampling frequency: $f_s \ge 2/T_{QRS}$
3. Duty cycling
$D = T_{active}/T_{total} \times 100\%$
4. Baud rate
$R_{baud} = R_{bit} / k$, $k = \log_2 M$
k: Bits per Symbol; M: Modulation Order
5. Logic level shifter
unidirectional bidirectional





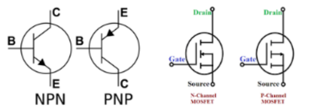
input-BJT-output
5V-close-3.3V
0V-open-0V

input-MOSFET-output
5V-close-3.3V
0V-open-0V

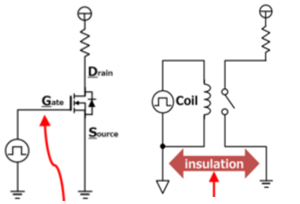
6. In vivo wireless communication
$L_{antenna} \approx \lambda_c/4$
$\lambda_c = \frac{v_p}{f_c} = \frac{v_0}{\sqrt{\mu_r\varepsilon_r}} \times \frac{1}{f_c} \doteqdot \frac{v_0}{\sqrt{\varepsilon_r}} \times \frac{1}{f_c}$
λ_c: Wavelength of carrier; v_0: Wave speed in vacuum; μ_r: Relative permeability (相对介电常数); ε_r: Relative permittivity

Week9

1. Amplifier Switch

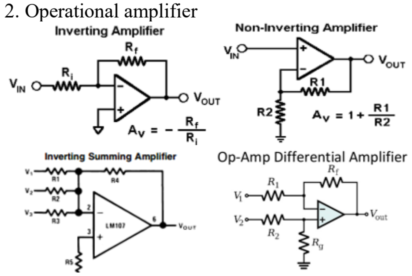


NPN: V_B 高 开
N-channel : $V_{GS} > V_{th}$ 开

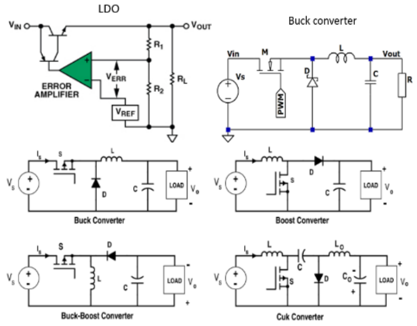


Transistor: Input and output are not insulated
Relay: Input and output are insulated

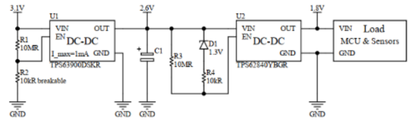
2. Operational amplifier



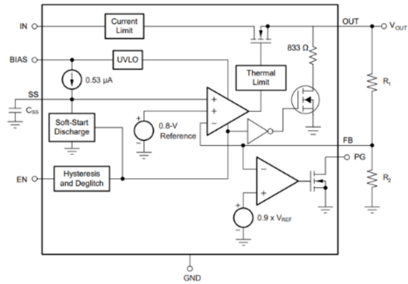
$V_{OUT} = -R_4\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right)$ $V_{OUT} = \frac{(R_f+R_1)R_2}{(R_4+R_2)R_1}V_2 - \frac{R_f}{R_1}V_1$
3. Pulse width modulation (PWM)
$V_{OUT} \approx V_{in} \cdot D$, D: duty cycle
4. LDO low dropout regulator vs DC-DC converter



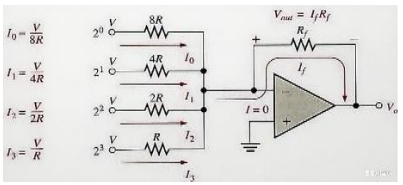
$v_{in} \cdot i_{in} = \eta \cdot v_{out} \cdot i_{in}$ $v_{in} \cdot i_{in} = \eta \cdot v_{out} \cdot i_{out}$
$v_{out} = v_{ref}(1 + R_1/R_2)$ $D = v_{out}/(v_{out} + v_{in})$
$V_o = D \cdot V_s$ $V_o = V_s/1 - D$
$V_o = -D \cdot V_s$ $V_o = D \cdot V_s$
5. Super caps buffering circuit



6. TPS74201 (Soft Starter)

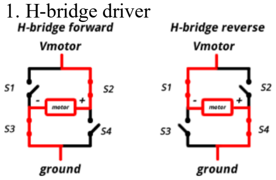


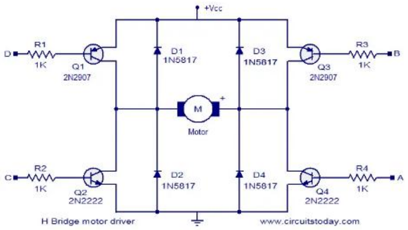
C_{ss}从 0.53uA 处储能后缓慢放电， $C_{ss}\uparrow$ $T_{start}\downarrow$
7. Digital to analog converter



Week10

1. H-bridge driver





Week1

Sensor 定义

A sensor is a device that detects and responds to input (stimulus) from its physical environment.

Physical Changes ->Sensor->Output Signals

Week 2 光学传感器 Optical Biosensor

. Fluorescence intensity is defined as the amount of photons emitted per unit timeand per unit volume of solution

. Brightness

-Brightness=εxΦ

光栅(grating) 角度分光能力 单位角度内有多少波长成分 d 角度/d 波长

分光能力越大越好，在一个角度内要包含更少的波长成分

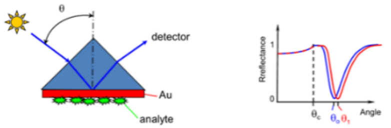
Week 3 Resonator 共振光学传感器

Surface Plasmon Resonance

纳米结构下的缝，会让光密度变大，用 Al, Ag, Cu, Au 生成 plasmonic，当激光照射金属表面，会吸收特定波长的光发热，形成一个波谷 dip dark signal 暗信号

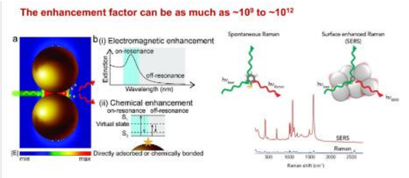
改变外部浓度，比如特定病毒附着，dip 会发生偏移，可能是激光角度也可能是波长 Localized Surface Plasmons 把金属 film 变成细小颗粒

拉曼散射 SERS surface enhanced Raman Scattering



金属纳米颗粒靠近或化学键有自己的 bend 会发生共振，在某些波长下会出现 peak 或 dip，增强拉曼散射，使信号放大

Week4 成像技术



Penetration depth 光信号深入人体组织深度后，信噪比为 1 的深度；红外对人体组织的穿透更深，用于计算心跳，血氧饱和度，利用血红蛋白携带氧气后的吸收差异

Optical Coherence Tomography OCT 主要用于眼科检测，发射后，距离的细微差异带来相位差，图像主要与反射率有关。是眼睛的纵切面成像

Hyperspectral Imaging 包含更丰富的光谱，全波长的信息（传统的只包含 RGB 三个波长的信息），扫描成像

Week 5 非光学成像技术

Ultrasound Imaging 基于反射，声波频率只有百 Khz，因此频率比光低，波长更大，身体不同组织对超声波的衰减是不同的，且与频率有关，深度定义也是信噪比为 1 的地方。但是超声波是反射的，要计算来回的距离。因此实际深度是一半。

声光成像 Photoacoustic Imaging 声和光的优势，声更深入，光分辨率更高

laser pulse -> absorption -> thermal expansion -> acoustic waves -> ultrasound detection -> image formation

Week6 电化学传感器

化学氧化还原反应 Redox reaction 产生电子流，体液 blood, saliva 唾液,tears, urine, sweat

电压 Potentiometric，电流 Amperometric，阻抗 Conductometric 三种传感原理

电压是参考值，要有确定的 GND

Week7 人体电信号

对单个的 cell，可以用 patch electrode 直接插入细胞测试；也可以用微电极阵列 Multielectrode Array 测试

细胞表面电压神经细胞的内外压差是-70mv，由于钠钾泵，静息状态，内部 K 多，外部 Na 多

肌肉 EMG 电位用两个电极，测量两电极的差，有效降噪

心脏 ECG 的用三个电极，两臂和腿，由于心脏有吸血和泵血

脑电波 EEG 用 20 个电极在头的各个部位

LDO 用于低压降，纹波小，电阻分压原理

DCDC 用于高压降，纹波大，但是效率很高，PWM 分压

计算反馈电阻 Vout=Vref*(1+R1/R2)，计算软启动时间 Q=CV=It 恒流源给外部电容充电到 Vref 所耗费的时间即软启动时间，10ms 左右；超级电容放电，E=0.5*C*V^2

H 桥驱动

二极管作用续流，电极可视为一个大电感，停转时候会有反向的巨大电压，防止烧毁