

Metal-Free Electro-Optic Polymer Modulators and Sensors

A Qualifying Exam Presented to the
Faculty of The Viterbi School of Engineering
University of Southern California

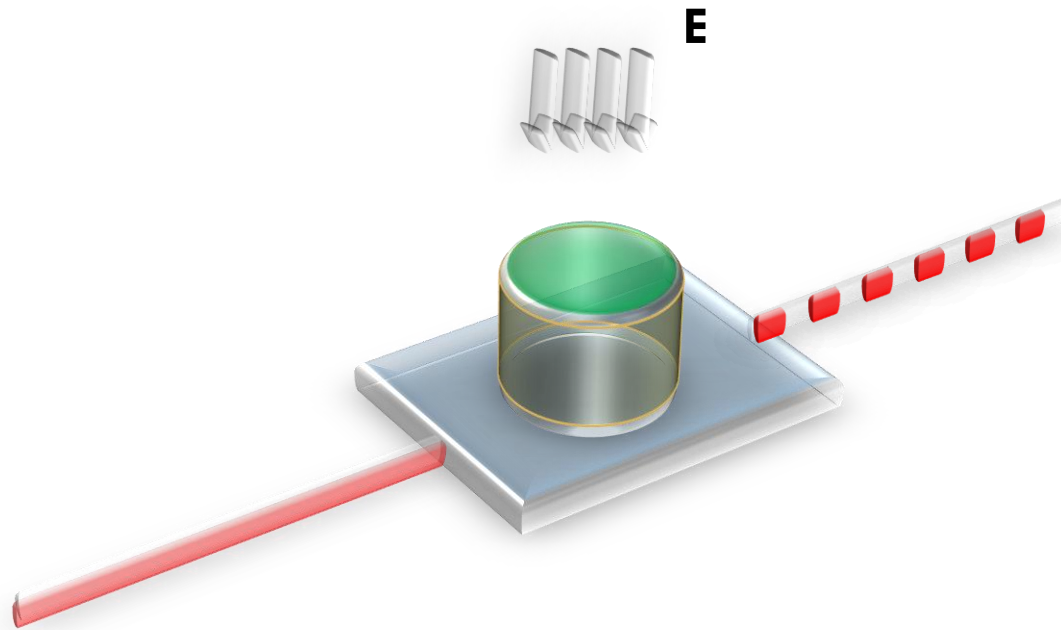
In Partial Fulfillment of the requirements for the Degree of Doctor of Philosophy

Committee in Charge:

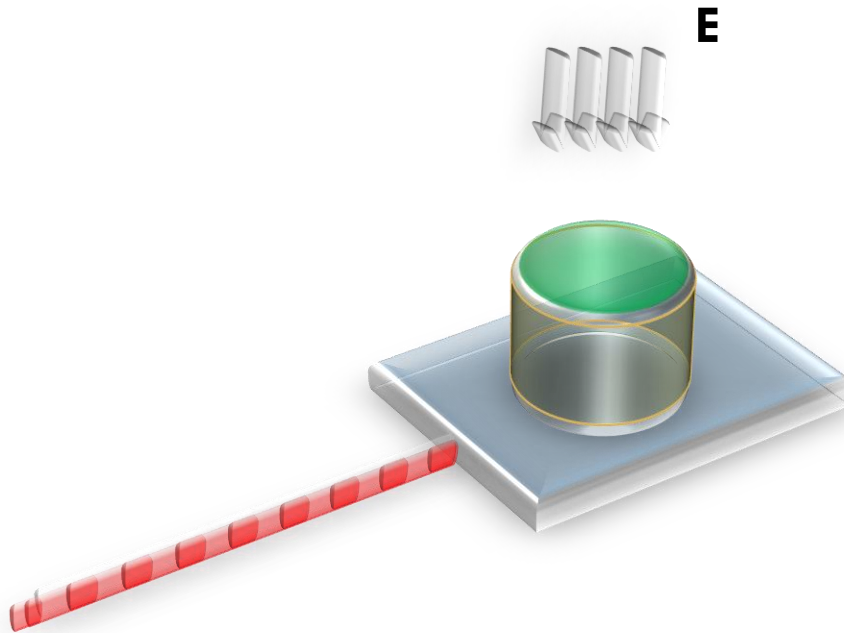
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Wednesday August 22, 2007 (2pm) SSC505

Nutshell



Nutshell



Outline

- **Introduction, Background and Motivation (9 slides)**
EO Polymers, EO Devices, Why Metal-Free?, Lift-Off Poling
- **Device #1 All-Dielectric Non-Electronic Radio Front-End (ADNERF) (9 slides)**
integrate an EO ring resonator into an all-dielectric 10GHz microwave receiver
- **Device #2 EO Ring Resonator Field Sensors (3 slides)**
an EO ring resonator for electric field mapping, with sensing areas $0.1-1\text{mm}^2$
- **Device #3 EO Reflection Grating Field Sensors (7 slides)**
an EO retroreflective grating for electric field mapping, with sensing areas $<0.02\text{mm}^2$
- **Conclusion**



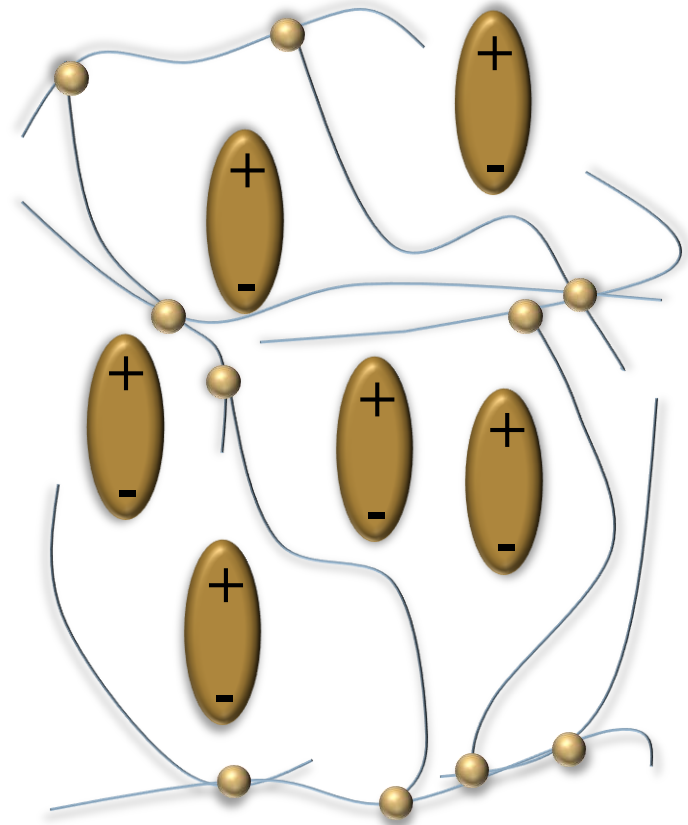
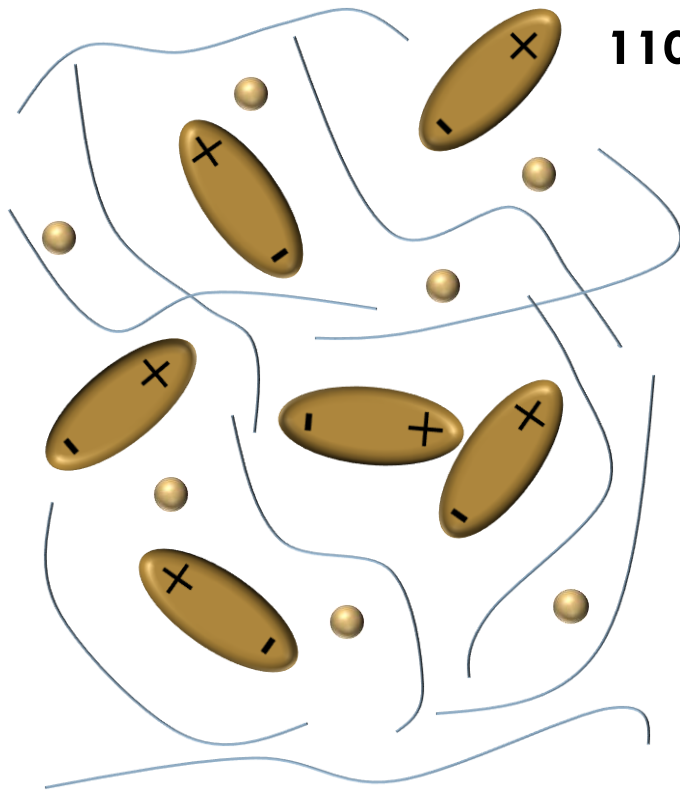
Introduction, Background and Motivation

EO Polymers, EO Devices, Why Metal-Free?,
Lift-Off Poling, Design Considerations

Electro-Optic Polymers

+80-120V/ μm

110-140°C



GND

Electro-Optic Polymers

Figure of merit:

	LiNbO ₃	EO Polymer
n	2.1	1.7
r	31	380
ϵ	30	2.8
$n^3 r / \epsilon$	9.6	650

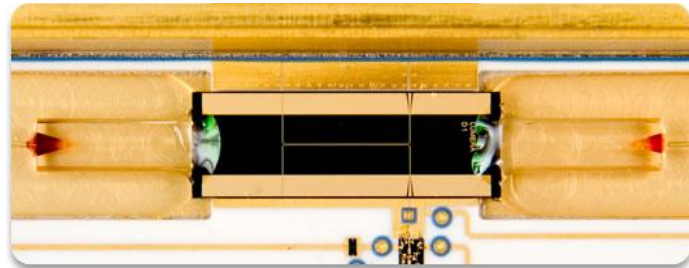
Why polymers?

- molecularly engineerable
 - electro-optic effect
 - optical loss
 - electrical conductivity
- physically flexible
- large thermal-optic effect
- simpler fabrication processes
- low permittivity

Why not?

- photostability
- thermal stability

Polymer Electro-Optic Devices: Modulators

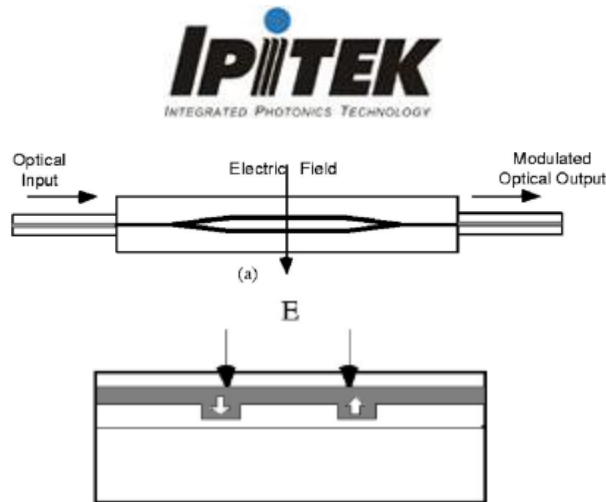


	20 GHz	40 GHz	100 GHz	20GHz
Insertion Loss	10 dB	7 dB	5 dB	5dB
V_{π} at 3 KHz	1.5 V	3 V	5 V	5V

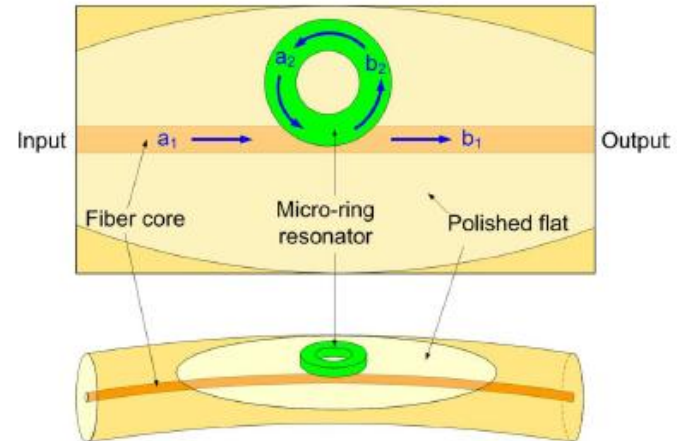
EO Polymer Modulator Research:

- 20GHz modulator, $0.36V_{\pi}$ at 3 KHz, but insertion loss = 21 dB
- -3dB, 165GHz modulation bandwidth on a travelling wave ring resonator
- Flexible modulator bent to $<5\text{mm}$ radius without effect on switching voltage/loss

Polymer Electro-Optic Devices: Sensors



Sensitivity = $70\text{mV}/(\text{m}\sqrt{\text{Hz}})$
 (0.08mm^2)
 (OE 45 (12), Dec 2006)



Sensitivity = $100\text{mV}/\text{m}$
 (0.019mm^2)
 (IEEE Sensors 7 (4), Apr 2007)

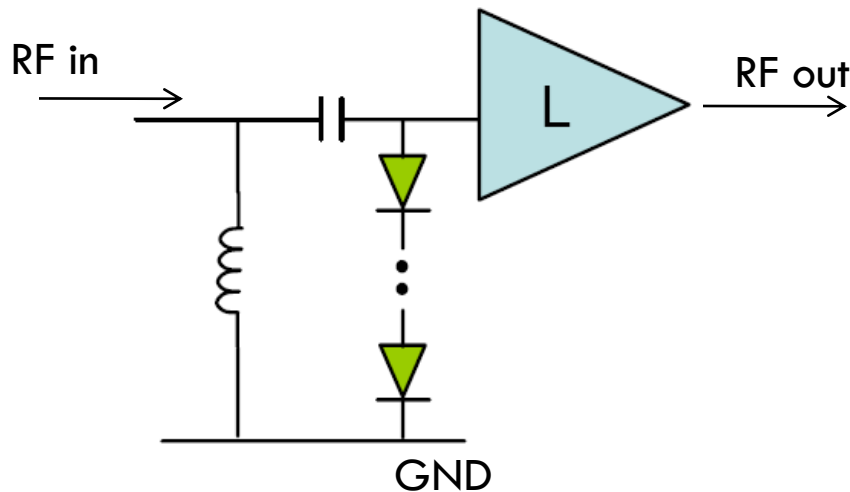
EO Polymer Sensor Merits:

- Large dynamic range, limited only by material breakdown $\sim 2 \times 10^8 \text{V}/\text{m}$
- Low permittivity = lower field shielding, $\epsilon_{\text{polymer}} = 2.8 < \epsilon_{\text{LiNbO}_3} = 30$
- Physically flexible

Why Metal-Free?

Graham Commission Report to the US Congress House Armed Services Committee (2004) concluded:

... the current vulnerability of U.S. critical infrastructures can both invite and reward that [HEMP] attack, if not corrected...



Other protection schemes

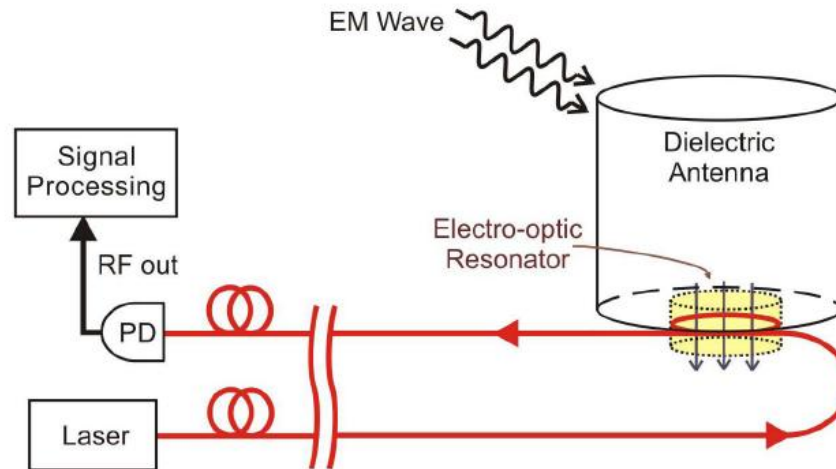
- plasma limiters
- gas discharge tubes
- ferrite limiter

Issues?

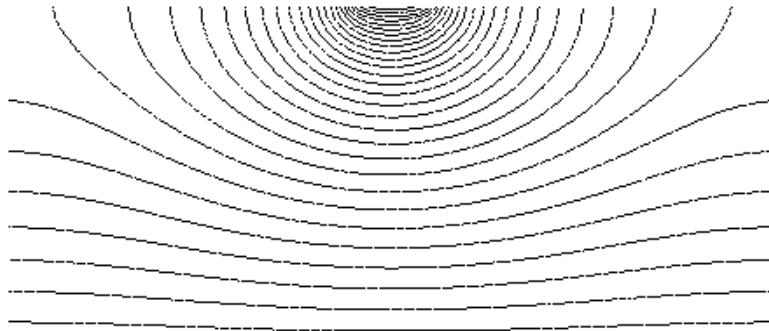
- receiver bandwidth limitations
- low power handling capability
- turn-on times too slow

Why Metal-Free?

An all-dielectric metal-free optical RF detector **fully isolates the detection circuitry** via a length of optical fiber, can **operate over a large bandwidth**, and possesses **"always on"** protection.

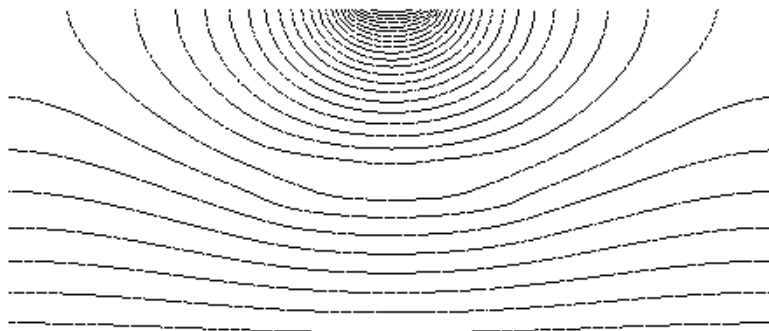


Why Metal-Free?

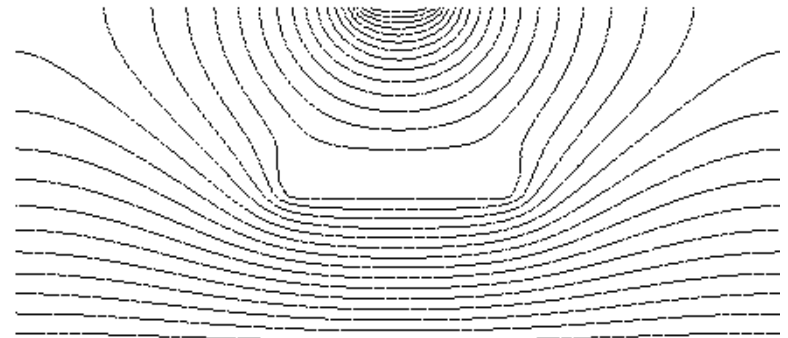


Unperturbed static field

- small detection area ($<1 \text{ mm}^2$)
- large dynamic range
- good sensitivity ($\text{mV}/\text{m}\sqrt{\text{Hz}}$)
- large bandwidth
- signal carried in optical fiber
- minimal influence on measured field



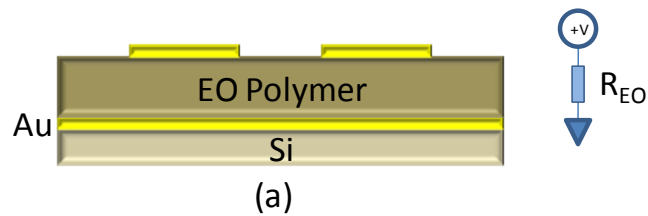
Dielectric probe $\epsilon_r = 2.8$



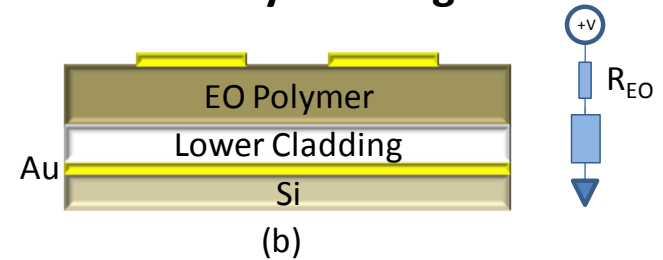
Metallic probe

Poling Conductivity Issues

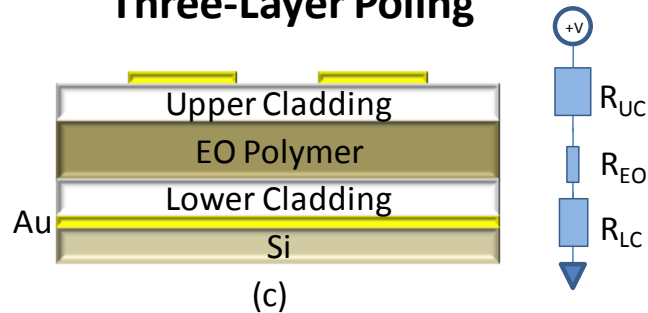
Single-Layer Poling



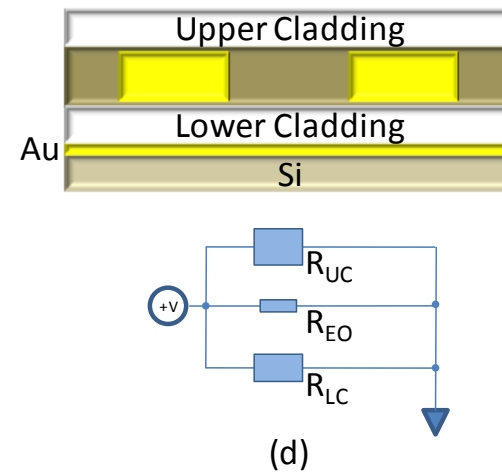
Two-Layer Poling



Three-Layer Poling

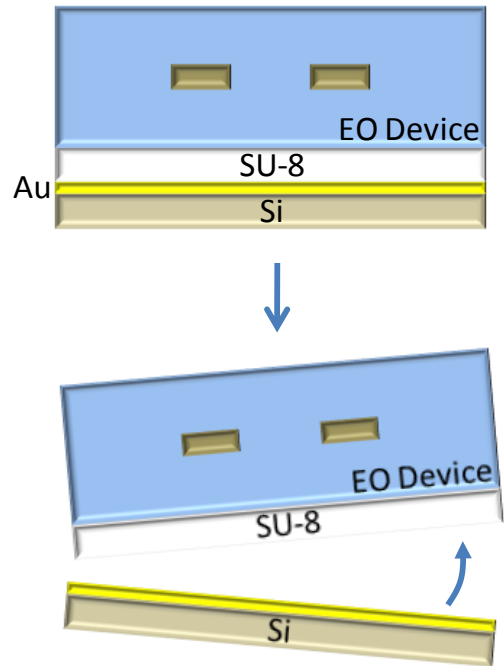


CPW Poling

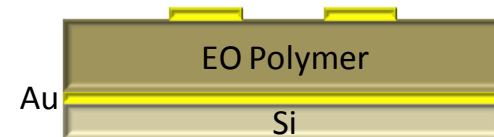


Lift-Off Poling

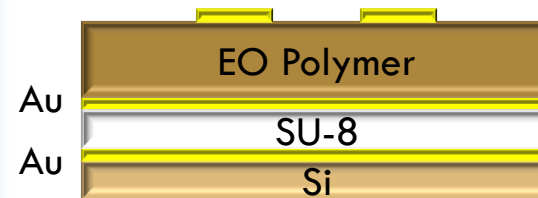
Lift-off



Single-Layer Poling



Lift-off Poling



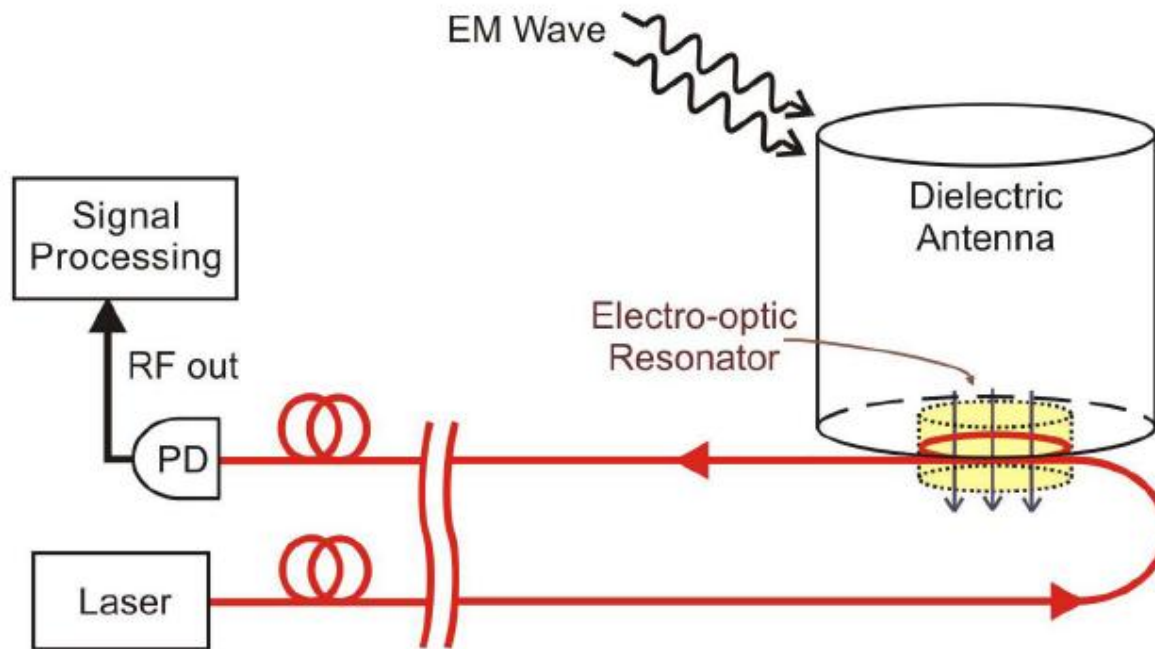


Device #1

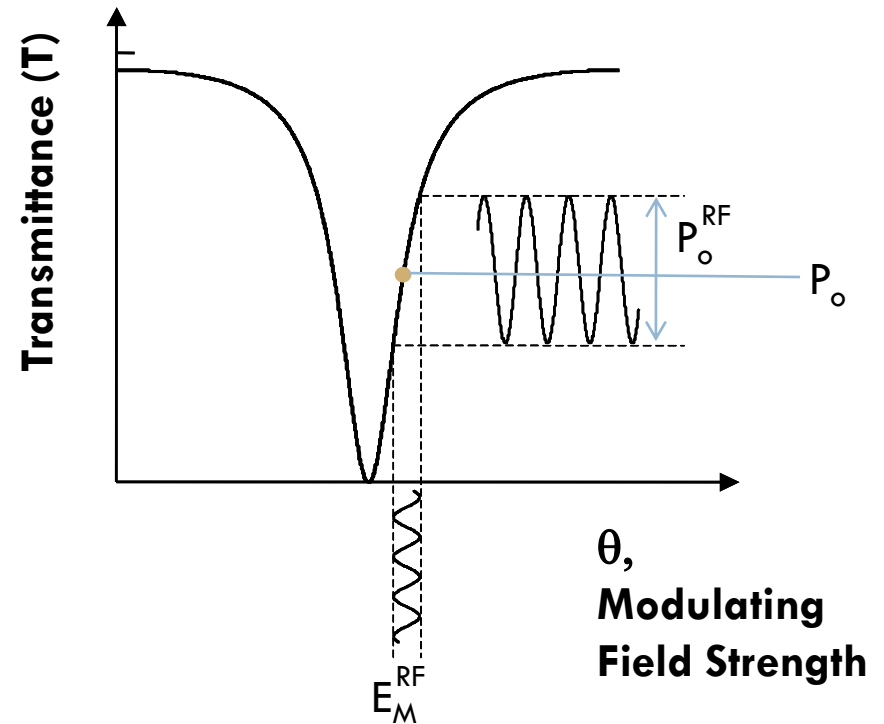
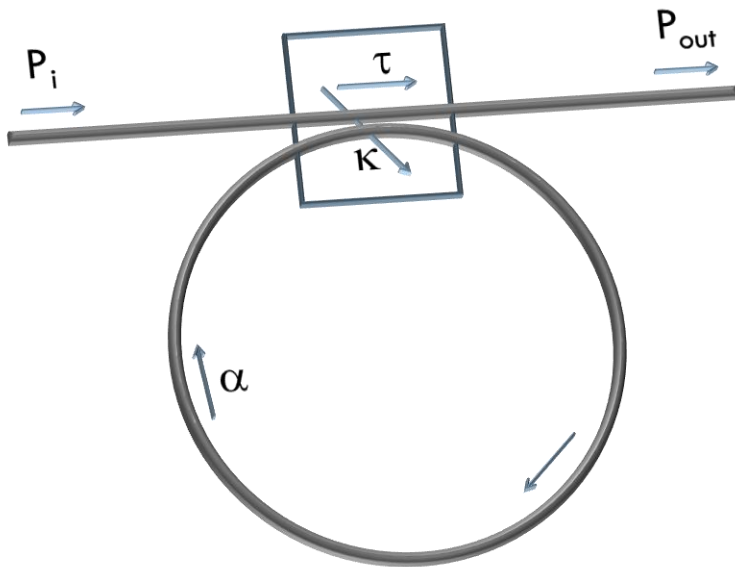
All-Dielectric Non-Electronic Radio Front-End (ADNERF)

Goal: integrate an optimized EO ring resonator into an all-dielectric 10GHz microwave receiver

All-Dielectric Non-Electronic Radio Front-End



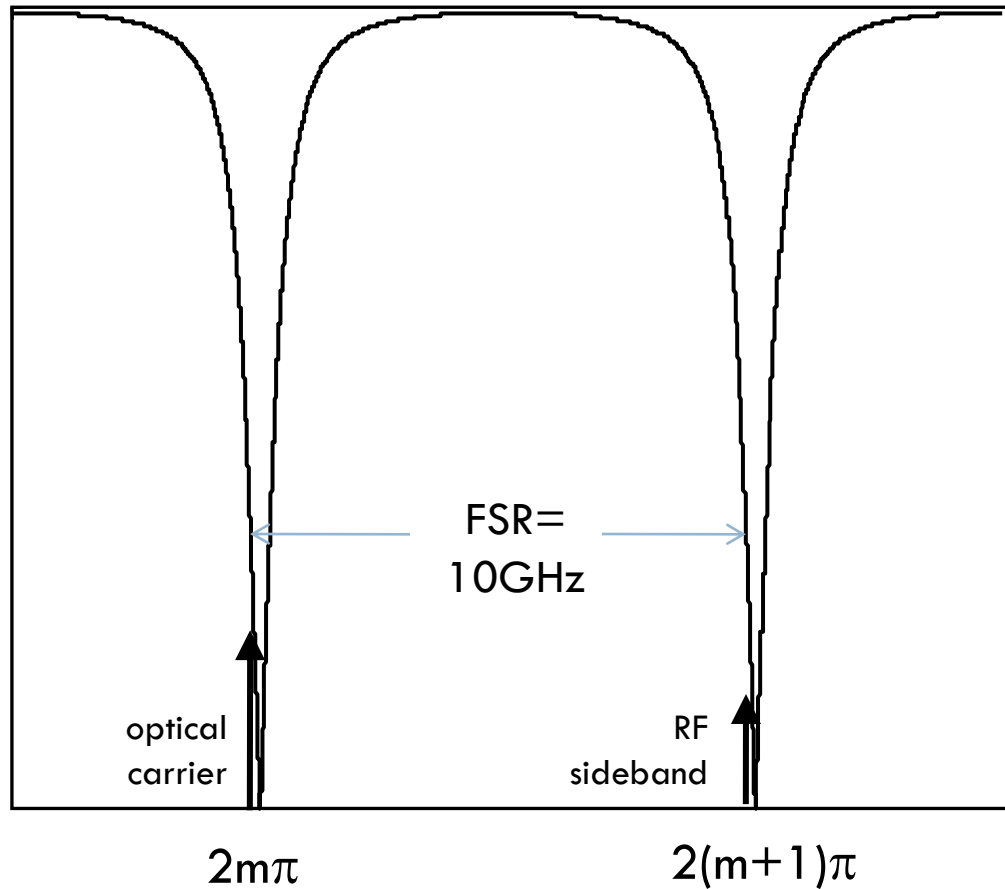
Electro-Optic Ring Resonator



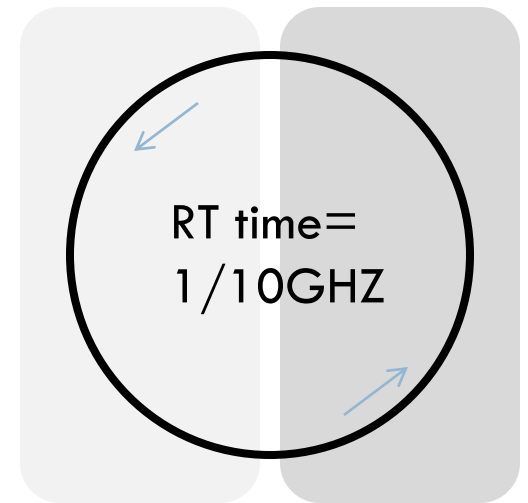
$$T(\theta) = 1 - \frac{(1 - \alpha^2)(1 - \tau^2)}{(1 - \alpha\tau)^2 + 4\alpha\tau \sin^2(\theta/2)}$$

Electro-optic Ring Resonator

T

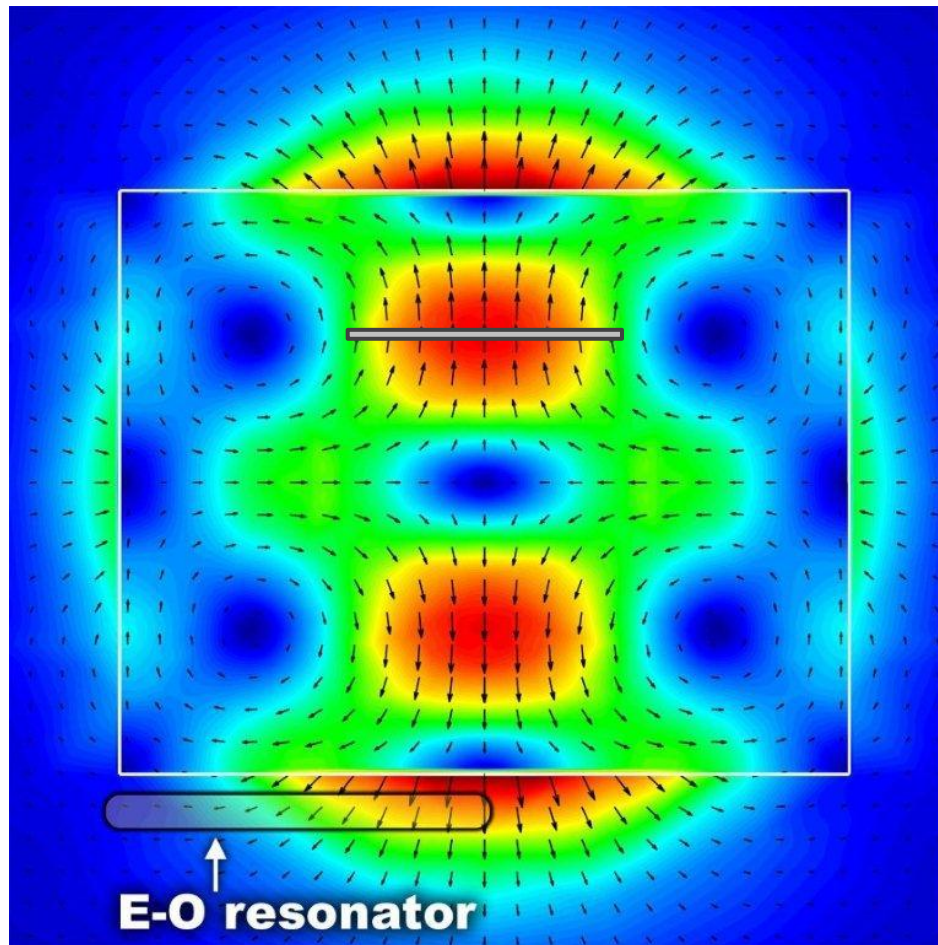


$$\text{FSR} = c/nL$$



θ

Dielectric Rod Antenna



7.38GHz excited $TM_{011+\delta}$

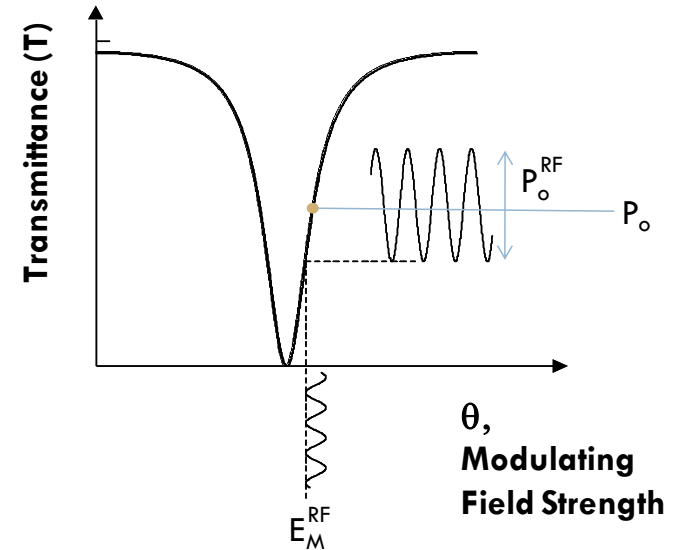
- field enhancement $\beta=25$
- additional $\epsilon_{\text{DRA}}/\epsilon_{\text{polymer}}=12$ enhancement
- two hotspots are 180° out of phase = differential detection

ADNERF Receiver Sensitivity

At the detector:

$$CNR = \frac{(mRP_o)^2 / 8}{\sigma_{RIN}^2 + \sigma_{shot}^2 + \sigma_T^2}$$

$$m = \frac{P_o^{RF}}{P_o}$$



RIN noise

shot noise

$$P_{min}^{RF} = \frac{\frac{A_e}{\eta_o} \left(\frac{(RP_o)^2}{2} 10^{\frac{RIN}{10}} + 2qRP_o \right)}{\left(\left[\frac{dT}{d\theta} \right]_{\theta=\theta_o} \frac{\pi n^3 r_{33} L}{\lambda} \zeta \frac{P_o}{T(\theta=\theta_o)} R \frac{\epsilon_{DRA}}{\epsilon_M} \beta \right)^2}$$

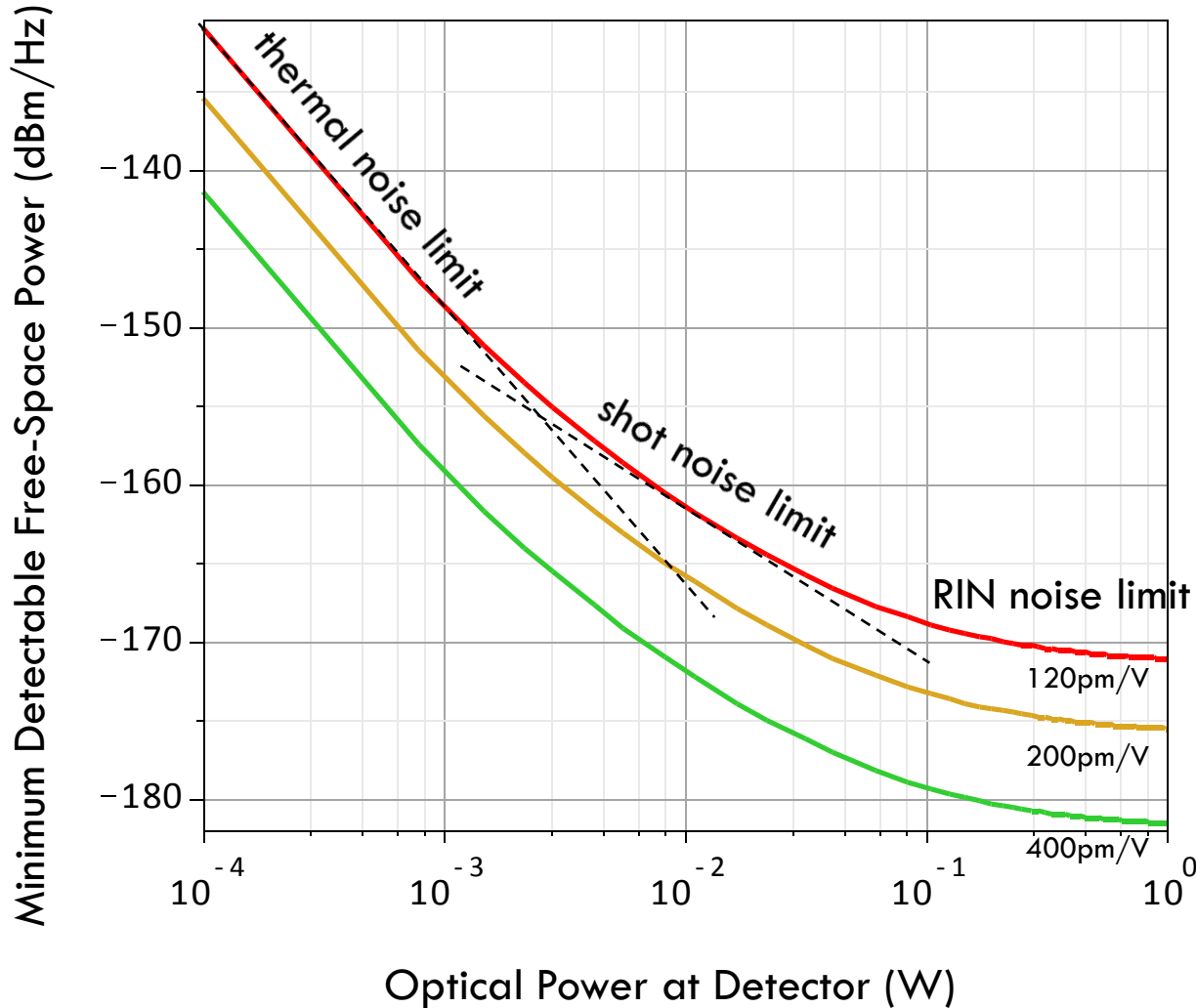
transmittance slope

EO material

laser power

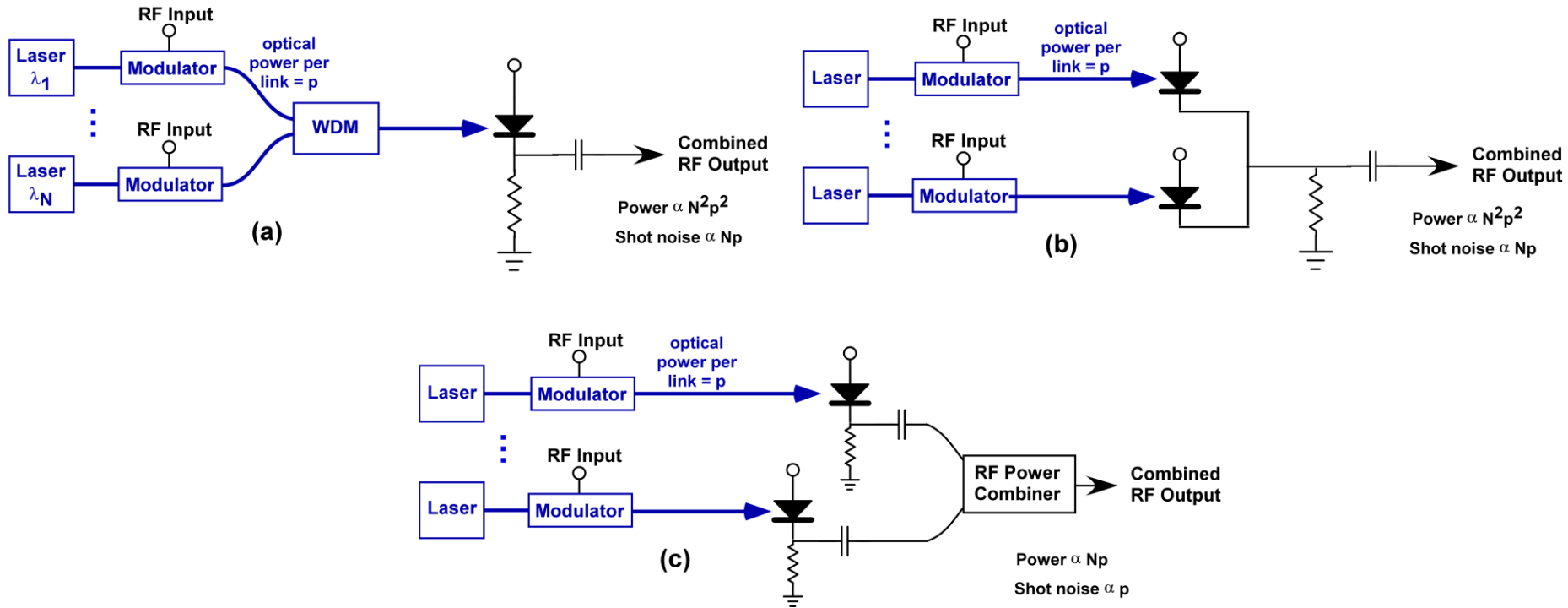
DRA material

ADNERF Receiver Sensitivity



$A_e = 10^{-4}$
 $\alpha = 2 \text{ dB/cm}$
 $\beta = 25$
 $\epsilon_{\text{DRA}} / \epsilon_{\text{M}} = 12$
 $\text{RIN} = -170 \text{ dB/Hz}$
 $R = 0.8 \text{ A/W}$
 $\text{FSR} = 10 \text{ GHz}$

RF Power Combining



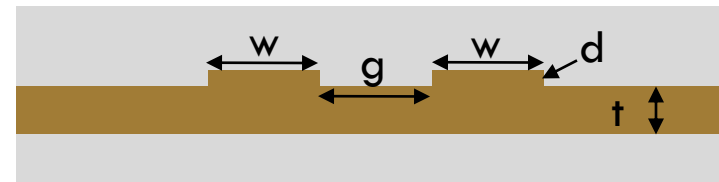
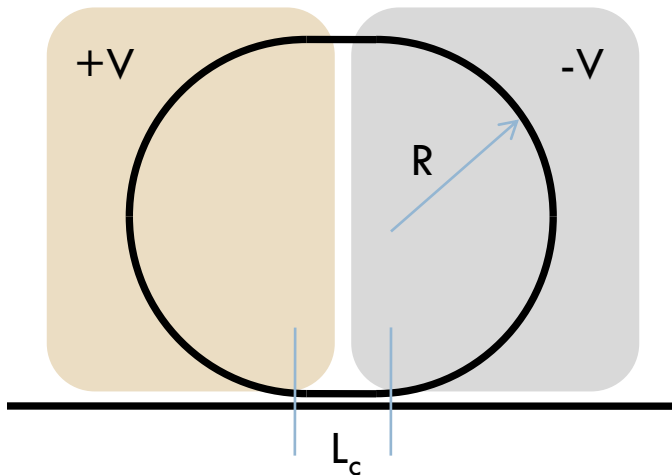
	Limiting Condition	RF Power	Shot Noise	CNR
(a)	Modulator Power	$\propto I_{tot}^2 = N^2 p^2$	$\propto Np$	$\propto Np$
(b)	Modulator and/or Detector Power	$\propto I_{tot}^2 = N^2 p^2$	$\propto Np$	$\propto Np$
(c)	Detector Current/Capacitance	$\propto I_{tot} = Np$	$\propto p$	$\propto N$

Receiver Bandwidth and Linearity

Optical modulation bandwidth = **~0.9GHz!** > ~250MHz possible from LiNbO₃
Therefore limited by DRA resonance width and not ring resonator.

Linearity (two-tone intermod) of a ring-resonator modulator at half-bias point is **-125.5dB** as compared to -109.9dB for a Mach Zehnder [22]

EO Ring Resonator Design



Parameter	Value
L_c , coupling length	0-150 μm , 100-400 μm
g , coupling gap	2 μm , 3 μm
R , ring radius	2.74-2.86mm
w , waveguide width	2 μm
d , etch thickness	1 μm
t , film thickness	1.5 μm

ADNERF Goals

The purpose of this work will be to investigate integration of EO polymer ring resonant structures into the ADNERF, both theoretically and in a working prototype.

- derive and numerically solve the exact expressions for optimizing the modulated output of an EO ring resonator for use in an RF analog link
- examine the useable modes of a DRA and the optimal size and geometry of a ring resonator (or pair of resonators) to take advantage of the maximum possible field enhancement
- identify and optimize the factors that improve the minimum detectable free-space power and compare the achievable sensitivities to existing receiver solutions
- examine the linearity of EO ring resonators at different bias points and determine the upper limit on bandwidth and dynamic range of the input RF signal
- investigate optical RF power combining schemes and employ the appropriate technique for EO ring resonators given their power handling limits
- create a working prototype of an optimized EO ring resonator for integration into the ADNERF concept



Device #2

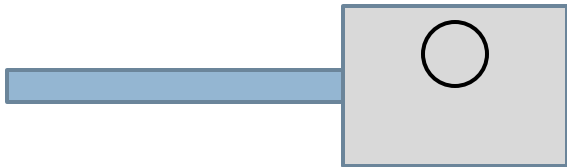
EO Ring Resonator Field Sensors

Goal: an optimized EO ring resonator for electric field mapping, with sensing areas $0.1 - 1 \text{ mm}^2$

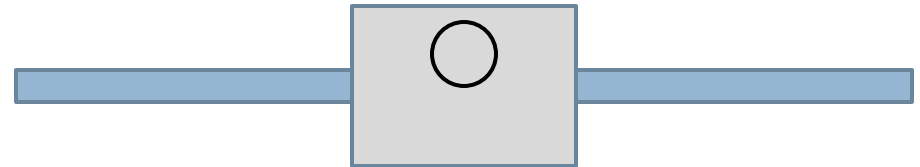
Ring Resonator Field Sensors

Same as ADNERF except

- signal modulated on the same resonance as optical carrier
- dielectric rod antenna is removed ($\gg 1$ mm)

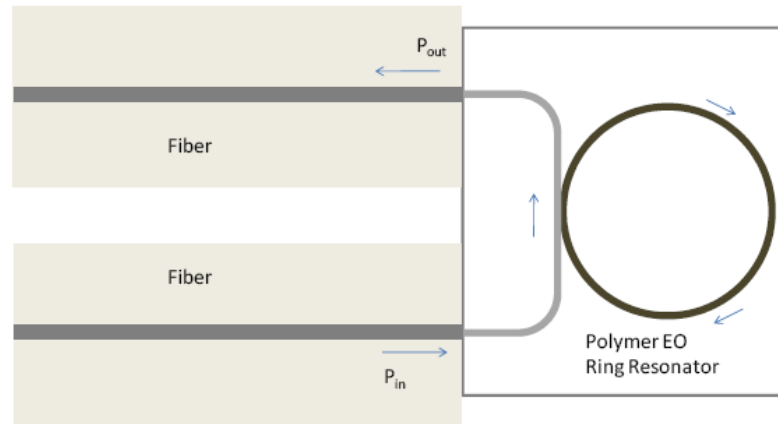


single-sided input/output

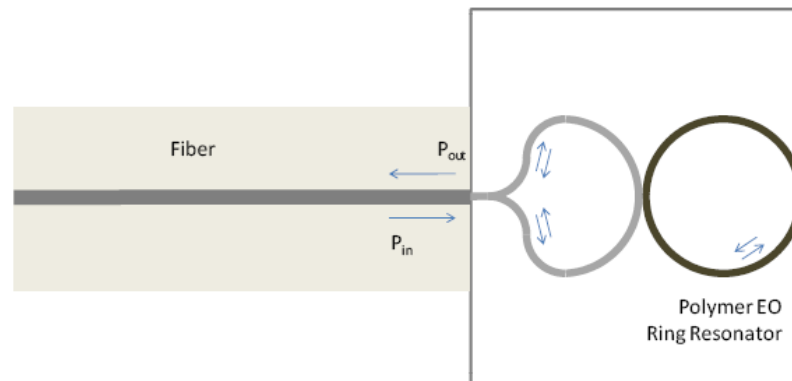


two-sided input/output

Ring Resonator Sensor Heads

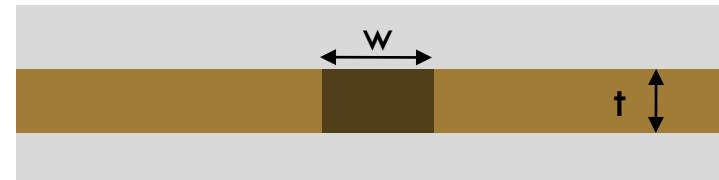
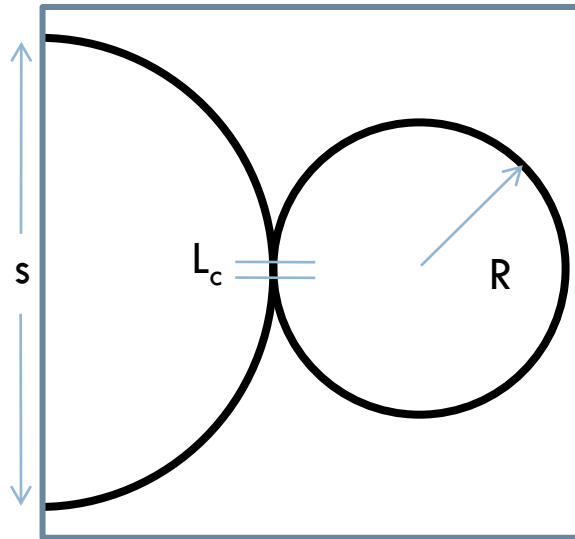


(a)



(b)

Metal-Free Field Sensor Design



- smallest ring radius with $\Delta n=0.07$ yields $300 \times 300 \mu\text{m}$ sensor
- estimated sensitivity = **$1.7 \text{ mV}/(\text{m}\sqrt{\text{Hz}})$**
- optical bandwidth is = **1.30 GHz**

Parameter	Value
L_c , coupling length	$0-20 \mu\text{m}$
Δn , waveguide contrast	0.07
R , ring radius	$150 \mu\text{m}$
w , waveguide width	$2 \mu\text{m}$
t , film thickness	$2.5 \mu\text{m}$
s , waveguide separation	1.05 mm

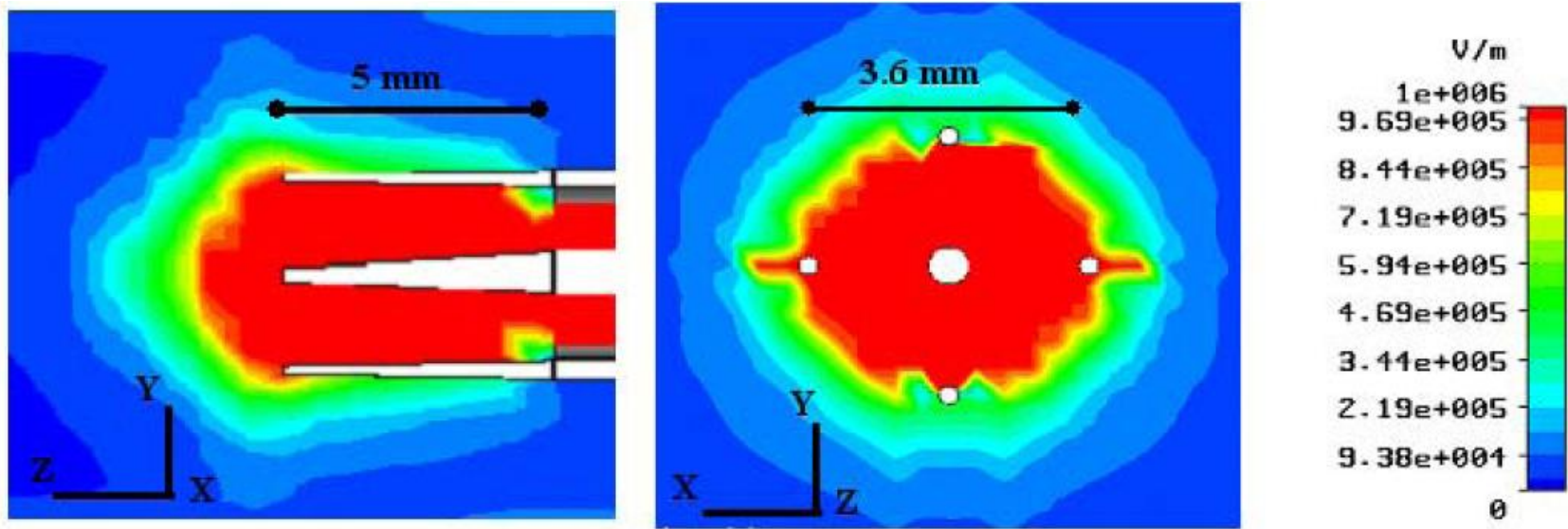


Device #3

EO Reflection Grating Field Sensors

Goal: an optimized EO retroreflective grating for electric field mapping, with sensing areas $<0.02\text{mm}^2$

Tight Geometry Field Measurement



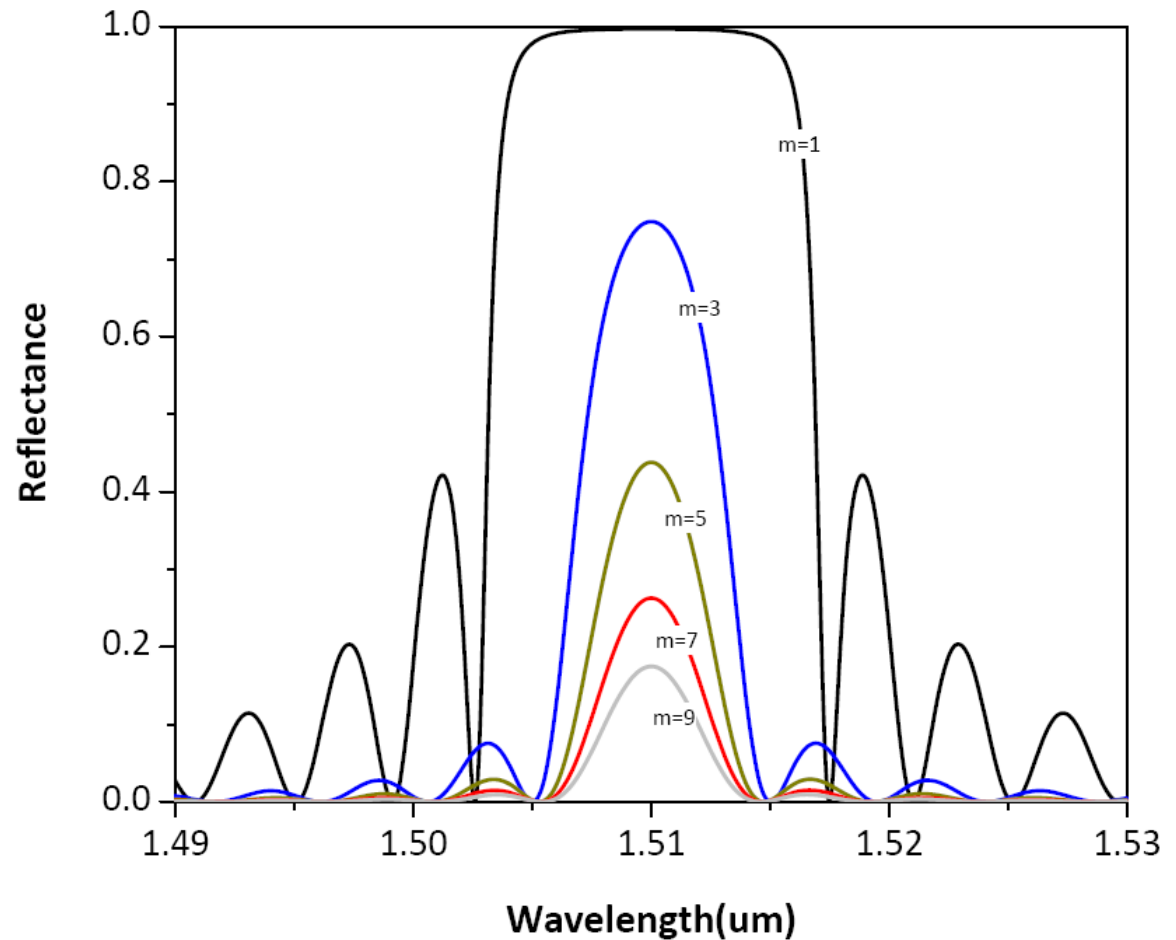
- up to 3MV/m fields
- 10-300 ns pulses
- resolve to 10% of geometry

RF pulse catheter field distribution, graphic courtesy of Cathy, Chunqi (Gunderson Group, USC)

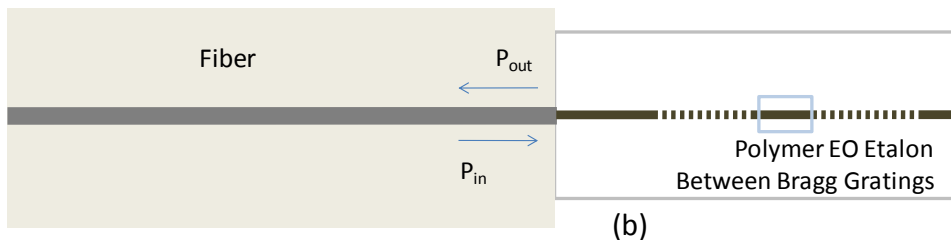
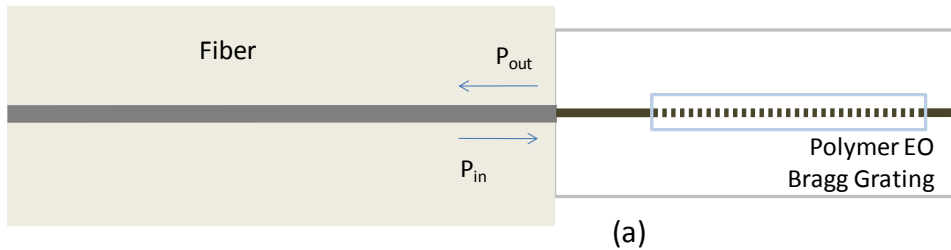
Grating Reflectance Response



- 150 μm length grating
- $\Delta n=0.02$
- center $\lambda=1.51\mu\text{m}$



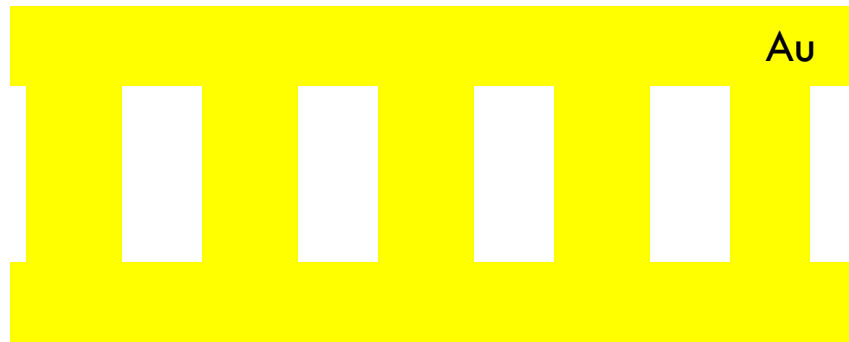
Retroreflective Grating Sensor Heads



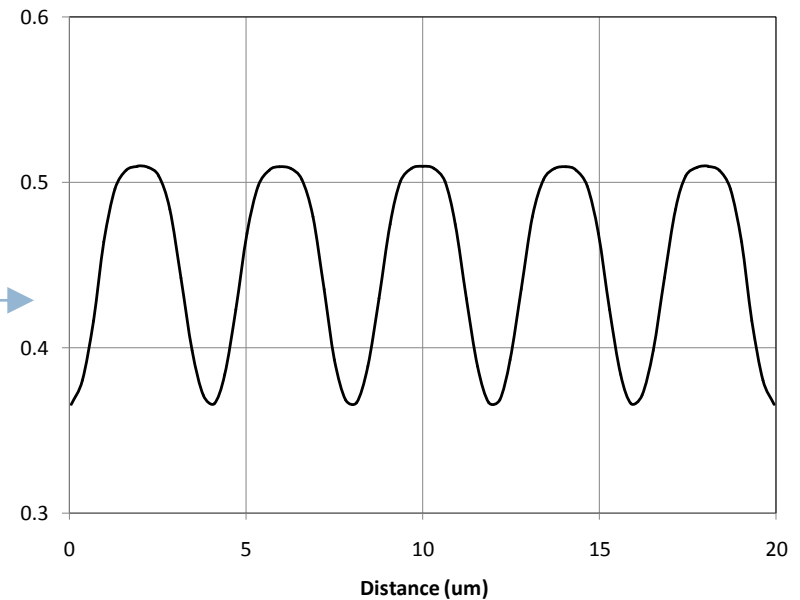
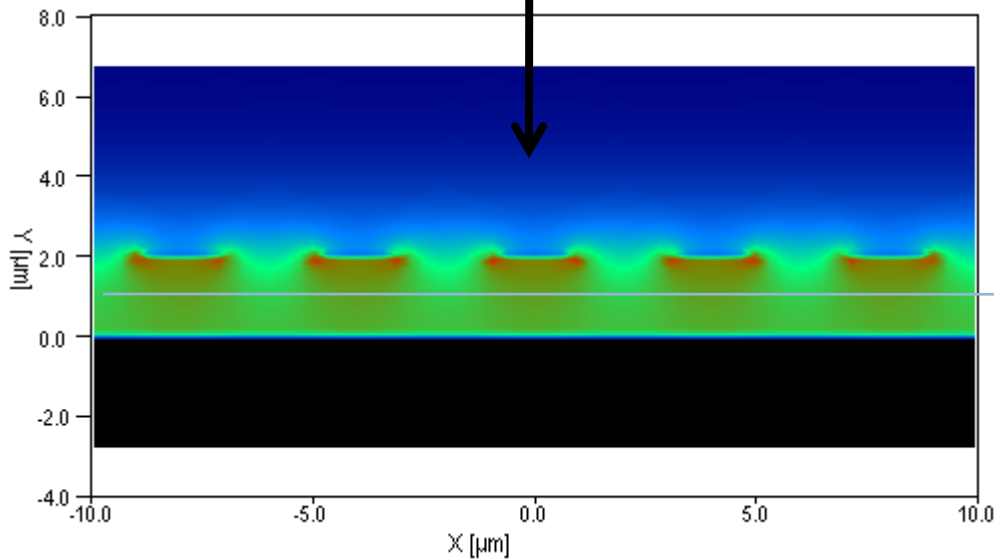
- sensitivity is $2V/(m\sqrt{\text{Hz}})$ for $m=9$ grating
- if $\text{BW}=\text{inverse pulse length}$:
 - $3.6\text{kV}/\text{m}$ for 300ns pulse
 - $20\text{kV}/\text{m}$ for 10ns pulse
- $>600\text{GHz}$ bandwidth
(estimated from group delay)

- sensitivity is $0.2V/(m\sqrt{\text{Hz}})$ for $R=0.5$
- $\text{BW}=10\text{'s of GHz}$
- survivability $>300\text{MV}/\text{m}$

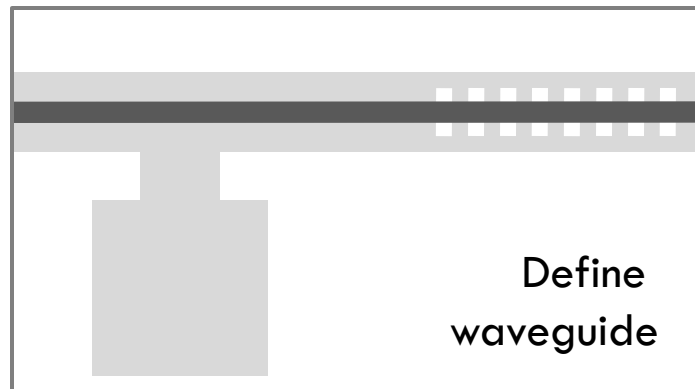
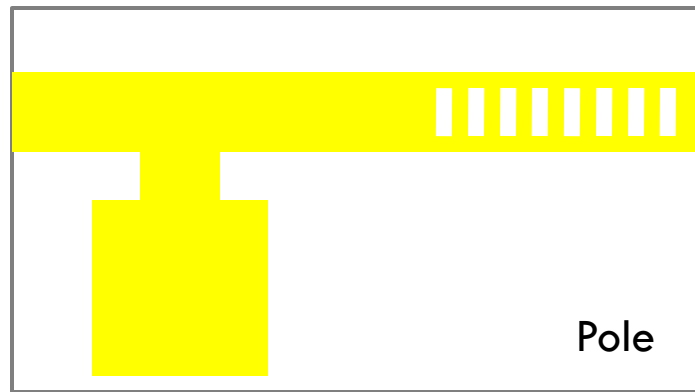
Index Grating via Poling



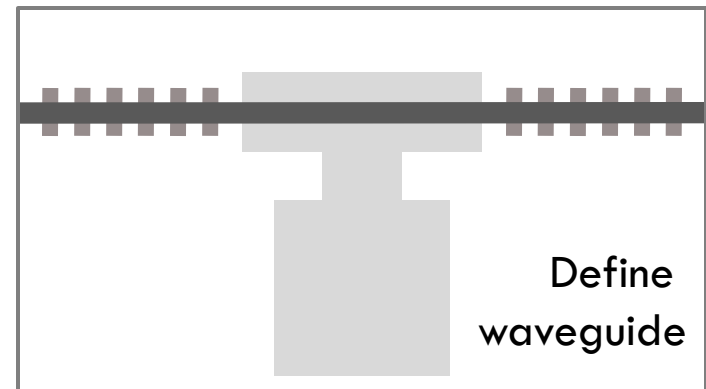
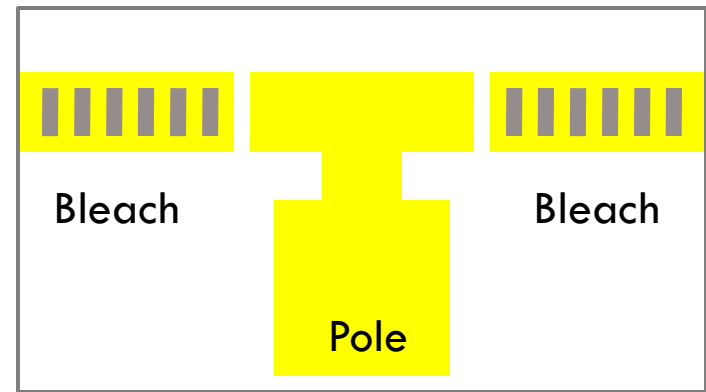
- $m=9$ grating, $\Lambda=4.12\mu\text{m}$
- $2\mu\text{m}$ -thick EO film



Grating Sensor Fabrication

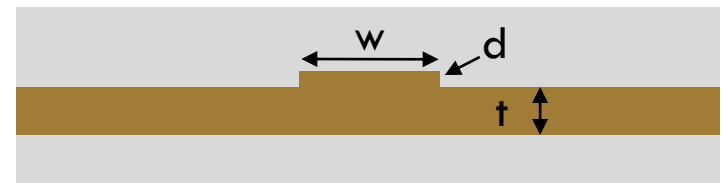
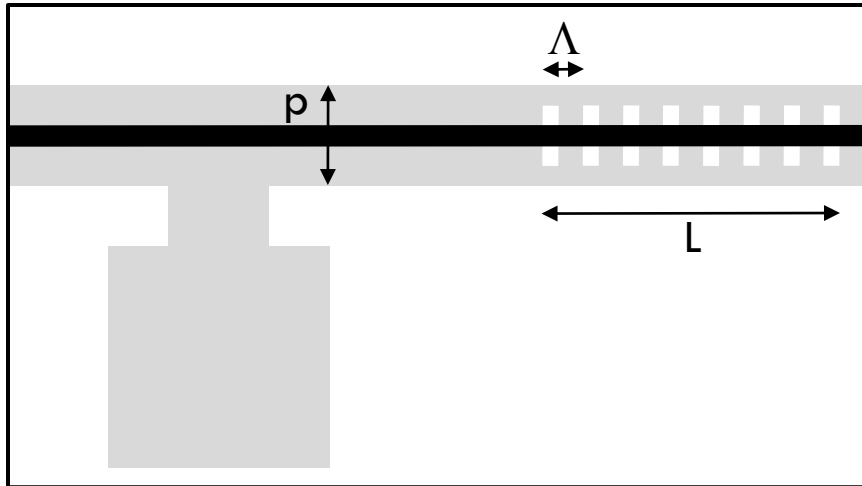


(a)



(b)

Grating Sensor Design



Parameter	Value
L, grating length	$150 \mu\text{m}$
Λ , Bragg period	$4.12 \mu\text{m}$
p, poled width	$25 \mu\text{m}$
w, waveguide width	$4 \mu\text{m}$
t, film thickness	$1.9 \mu\text{m}$
d, etch depth	$0.6 \mu\text{m}$

Field Sensor Goals

This work will investigate small area ($<1\text{ mm}^2$) electric field sensors and identify potential applications in high-resolution field mapping from DC to 10's of GHz.

- fabricate ring resonator based sensors with detector areas from $0.1\text{--}1\text{ mm}^2$ aiming at sensitivities in the $1\text{--}10\text{ mV}/(\text{m}\sqrt{\text{Hz}})$ range, for use from DC to the low GHz
- theoretically and experimentally investigate periodic poling and photobleaching of $m=1$ to $m=9$ index gratings
- fabricate retroreflective grating based sensors with detector areas $<0.02\text{ mm}^2$ aimed at sensitivities in the $1\text{--}10\text{ V}/(\text{m}\sqrt{\text{Hz}})$ range, for use from DC to the 10's of GHz

Conclusion

Theory Goals:

- Optimize ring resonator sensitivity, linearity and bandwidth
- Optimize retroreflective grating sensitivity, linearity and bandwidth
- Optimize integration with a dielectric rod antenna, examine RF power combining schemes

Fabrication Science Goals:

- Lift-off poling and compatible waveguide fabrication techniques
- Periodic poling and photobleaching of index gratings

Device Demonstration Goals:

- Integrate an EO ring resonator into an all-dielectric 10GHz microwave receiver and employ the appropriate optical RF power combining scheme to increase sensitivity
- Fabricate ring resonator based sensors with detector areas from 0.1 -1mm² aiming at sensitivities from 1-10 mV/(m[√]Hz), for use from DC to low GHz
- Fabricate retroreflective grating based sensors with detector areas <0.02mm² aiming at sensitivities from 1-10 V/(m[√]Hz), for use from DC to 10's of GHz

Device Design Considerations

Technique	Δn	Lift-off poling compatible?
Reactive Ion Etching	0-0.65	Yes
Molding	0.3-0.65	No
Wet Etching	0-0.2	No
Bleaching	- 0-0.02	Yes
Poling	+ 0.02-0.07	Yes

Limiting Factor	Min Radius
Single mode operation	300 μm
RIE scattering loss (reflow assumed)	200 μm
Max $\Delta n=0.09$	120 μm

Wide Waveguides (4-6 μm)	Narrow Waveguides (2 μm)
Large bending radius	Smaller bending radius
Good power coupling to fiber	Low power coupling to fiber
Lower scattering loss	High scattering loss
Better tolerance to fabrication error	Poor tolerance to fabrication error