SARNOFF Corporation

ECE·ILLINOIS
Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

Resonant Enhanced Modulator Development

J.H. Abeles
Sarnoff Corporation

DARPA/MTO R-FLICs Program: Kickoff Meeting

Hilton Arlington & Towers, Arlington, VA
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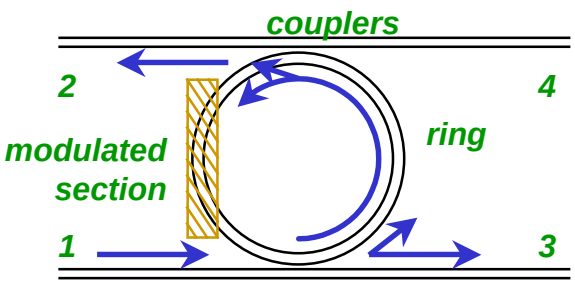
Review of this Material Does Not Imply Department of Defense Endorsement of Factual Accuracy or Opinion

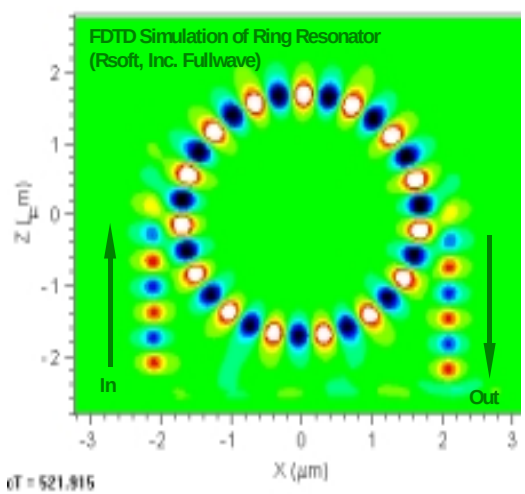
Modulator Needs

- Requirements for V_π Under 1 Volt
  - RF Photonics
    - High Dynamic Range
  - High Speed/Frequency/Bandwidth
    - $CV^2\Delta f$ Prohibitive Switching Power
  - Direct Connection to Antenna
    - Arrays
- Current Technology Inadequate (>1 Volt at ~ 10 GHz)
  - $LiNbO_3$
  - Electroabsorption
  - Polymer
- *Need: V_π in mV's, not Volts*

Double-Coupled Resonators



$$\left|\frac{\overline{E}_2}{\overline{E}_1}\right|^2 = \frac{k_1 k_2}{t_1^2 t_2^2 A^2 + 1 - 2 t_1 t_2 A \cos\phi_R}$$



$$\phi_{21} = \tan^{-1}\left(\frac{-t_1 t_2 A \sin\phi_R}{t_1 t_2 A \cos\phi_R - 1}\right)$$

$$\phi_R = (\beta + \Delta\beta)L$$

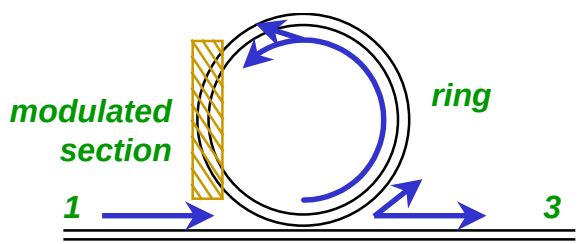
$$\beta = \frac{\omega}{c}\Delta n; \Delta\beta = \frac{\omega}{c}\Delta n$$

$$A = \exp^{-\alpha_{ampl} L}$$

$$k_{1,2} = power - coupling$$

Single-Coupled Resonators

$$\left|\frac{\overline{E}_3}{\overline{E}_1}\right|^2 = \frac{t^2 + A^2 - 2At\cos(\phi_R)}{t^2A^2 + 1 - 2At\cos\phi_R}$$



$$\phi_{31} = \tan^{-1}\left(\frac{A\left(t^2 - 1\right)\sin\phi_R}{t\left(A^2 + 1\right) - A\left(t^2 + 1\right)\cos\phi_R}\right)$$

$$\phi_R = (\beta + \Delta\beta)L$$

$$\beta = \frac{\omega}{c}n; \Delta\beta = \frac{\omega}{c}\Delta n$$

$$A = \exp^{-\alpha_{ampl}L}$$

$$t = \sqrt{1 - (power_coupling}$$

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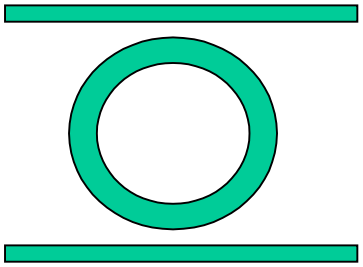
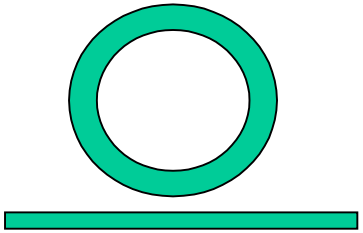
Ring Resonator Applications



Double-Waveguide Coupled Ring Resonator

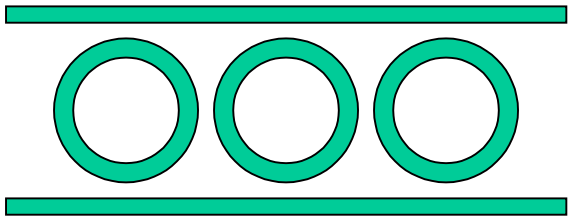
- **Tunable Filters**
- **WDM Add-Drop Multiplexers**
- **Ring Lasers**



Single-Waveguide Coupled Ring Resonator

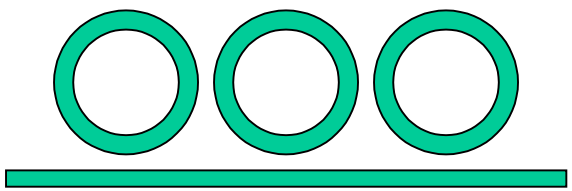
- **Frequency selective variable attenuators**
- **Frequency selective amplitude modulators**
- **Frequency selective phase modulators**

Ring Resonator Applications (cont'd)



Double-Waveguide Coupled
Multiple Ring Resonator

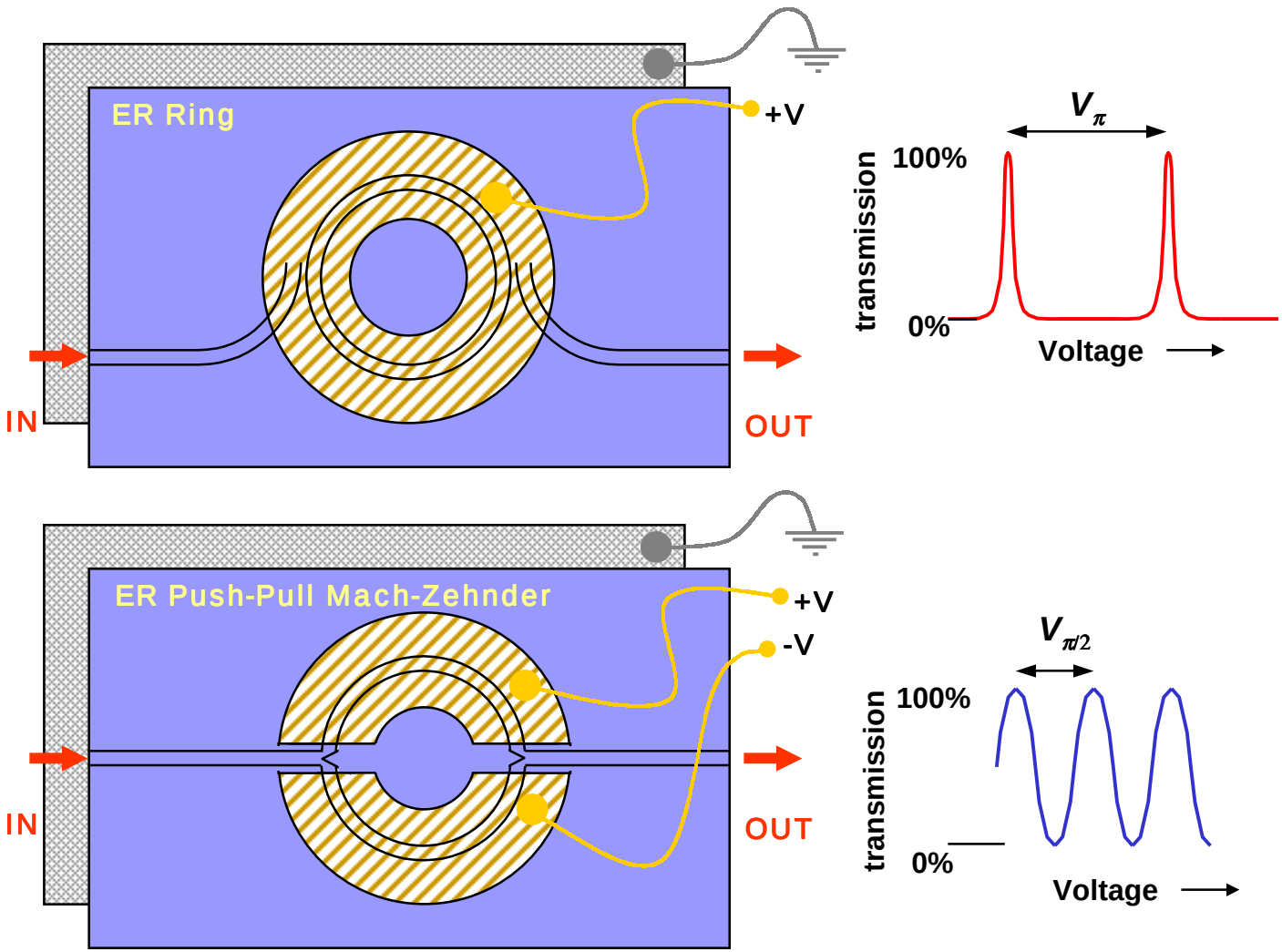
- **Flat-top Tunable Filters**
- **Flat-top WDM Add-Drop Multiplexers**



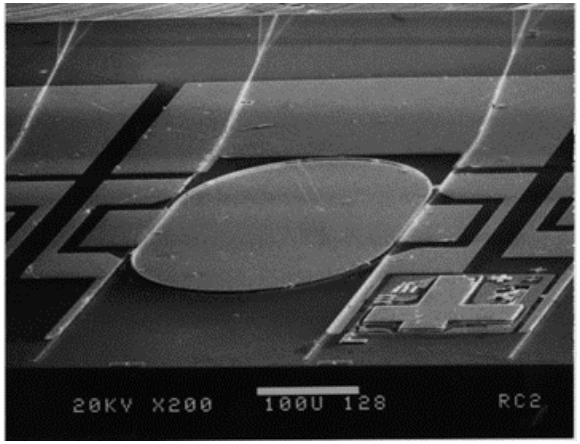
Single-Waveguide Coupled
Multiple Ring Resonator

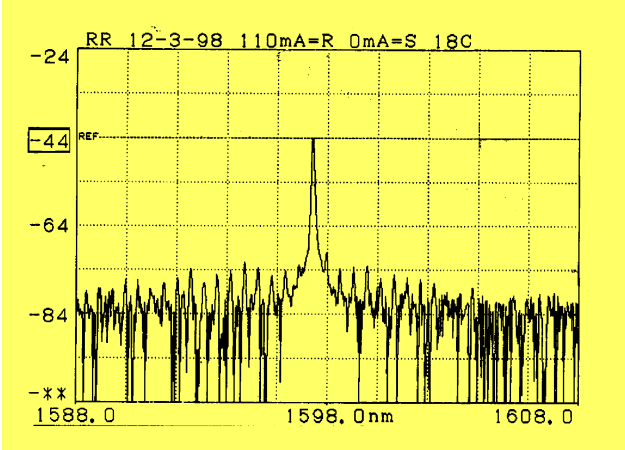
- **Multi-wavelength variable attenuators**
- **Amplifier gain equalizers**
- **Dispersion compensators**

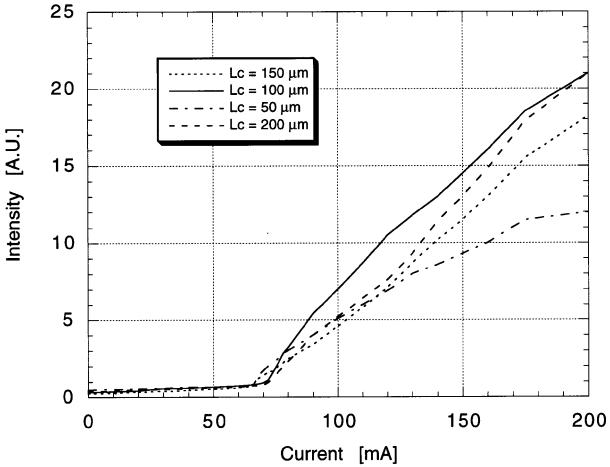
Ring Resonator vs. Mach-Zehnder



Record Low Threshold Ring Lasers







- **60 mA = I_{th}**
- **1550 nm**

Reactive Ion Etching at Illinois (UIUC)

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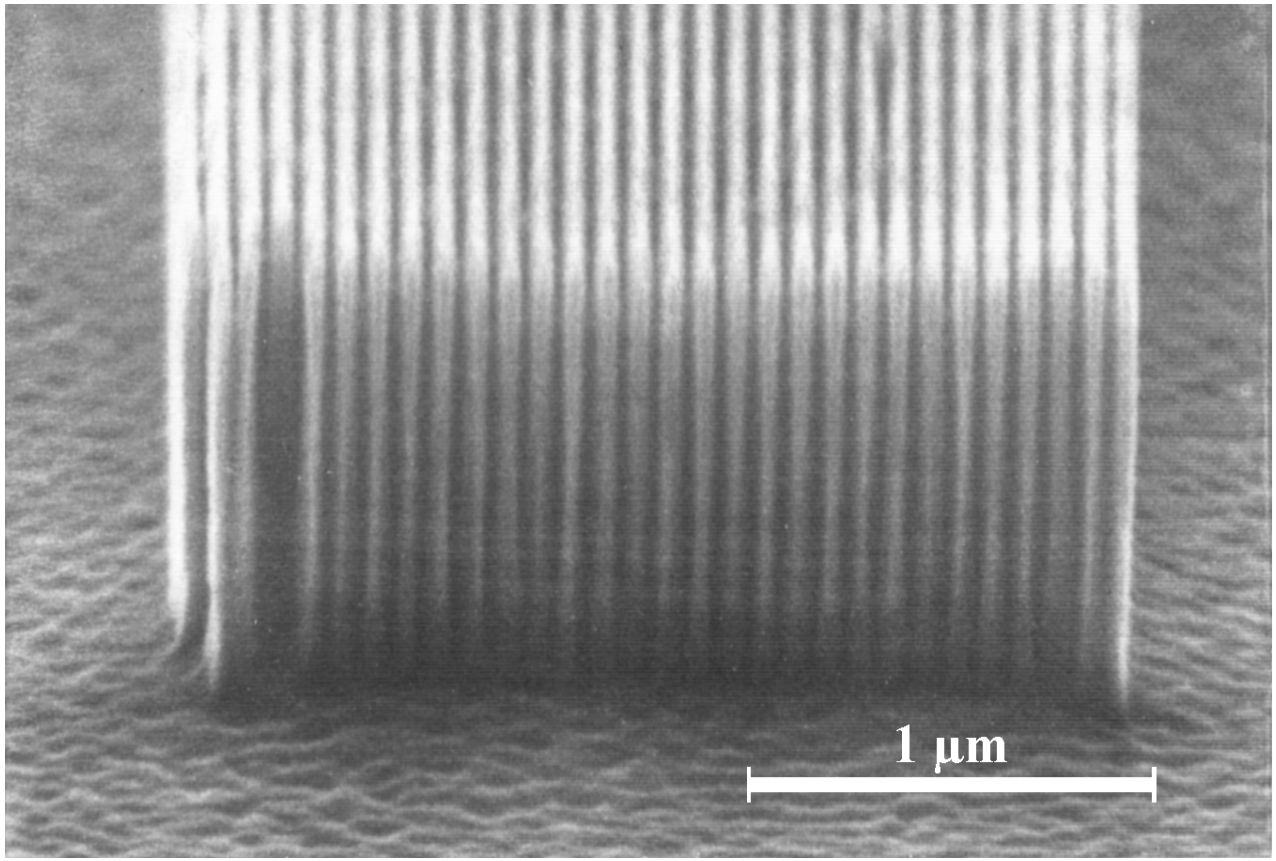
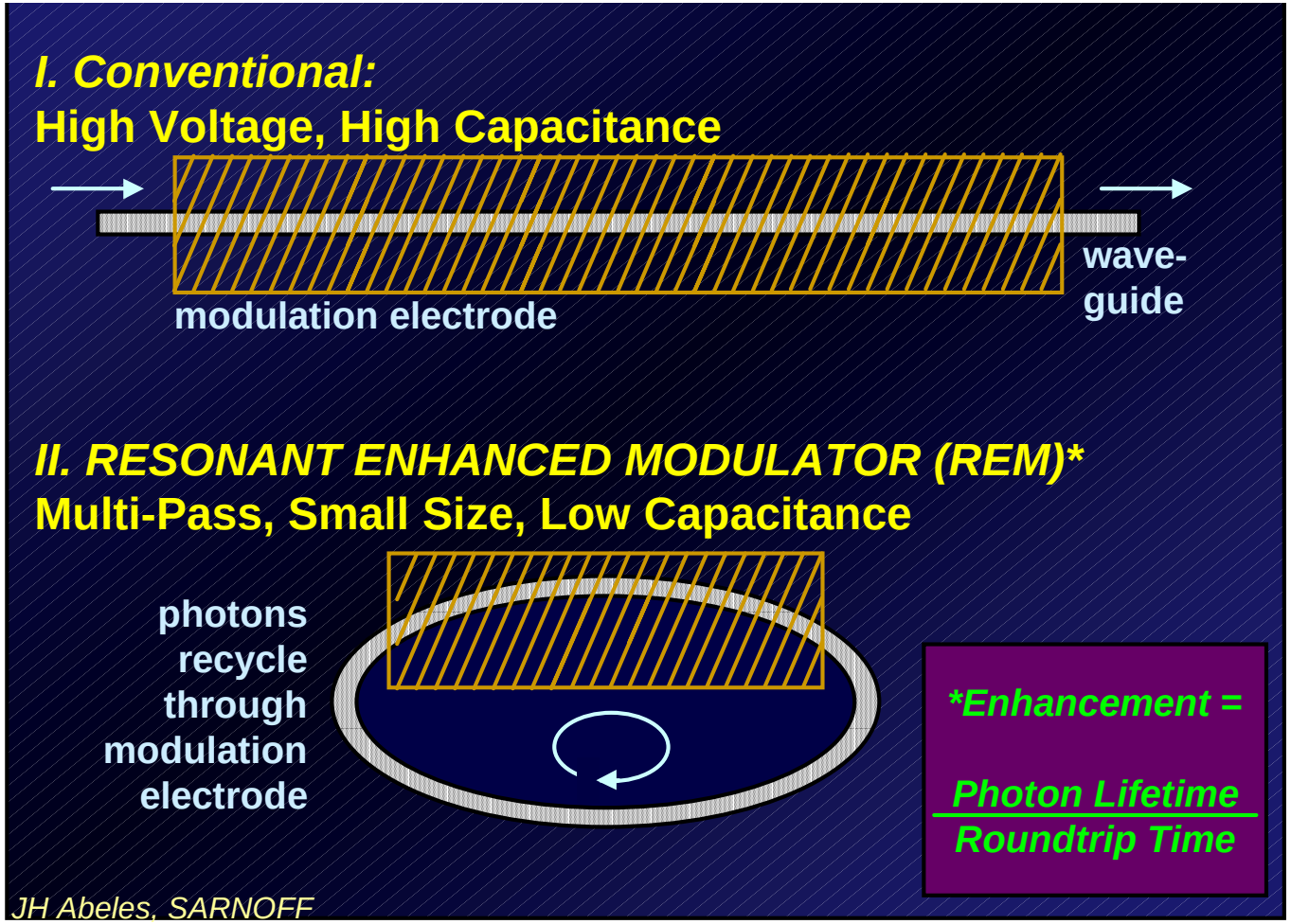


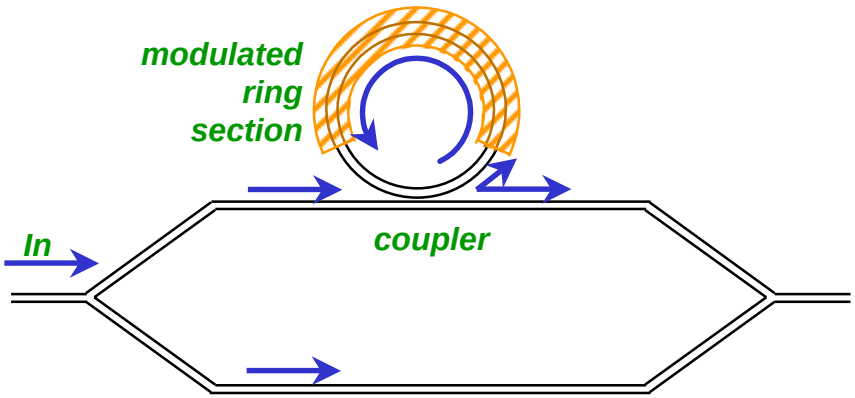
- CH_4-H_2 based
- 700 nm period

Photon Cycling Enhancement



Ring Resonator M-Z Modulators

- **Phase modulation due to coupled resonators**
- **Combine multiple resonators to achieve performance enhancement**



		Passband (GHz)			Photon Lifetime (psec)		
diameter	FSR	Finesse=	Finesse=	Finesse=	Finesse=	Finesse=	Finesse=
(um)	(GHz)	3	10	30	3	10	30
5	5968	1989	597	199	0.1	0.3	0.8
10	2984	995	298	99	0.2	0.5	1.6
20	1492	497	149	50	0.3	1.1	3.2
50	597	199	60	20	0.8	2.7	8.0
100	298	99	30	10	1.6	5.3	16.0

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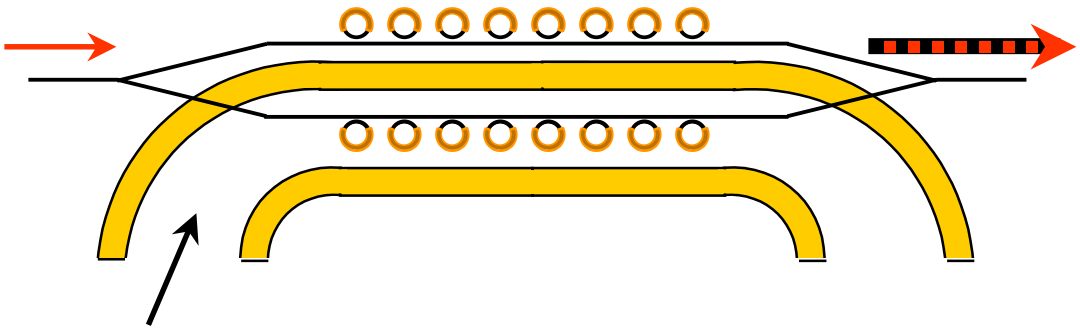
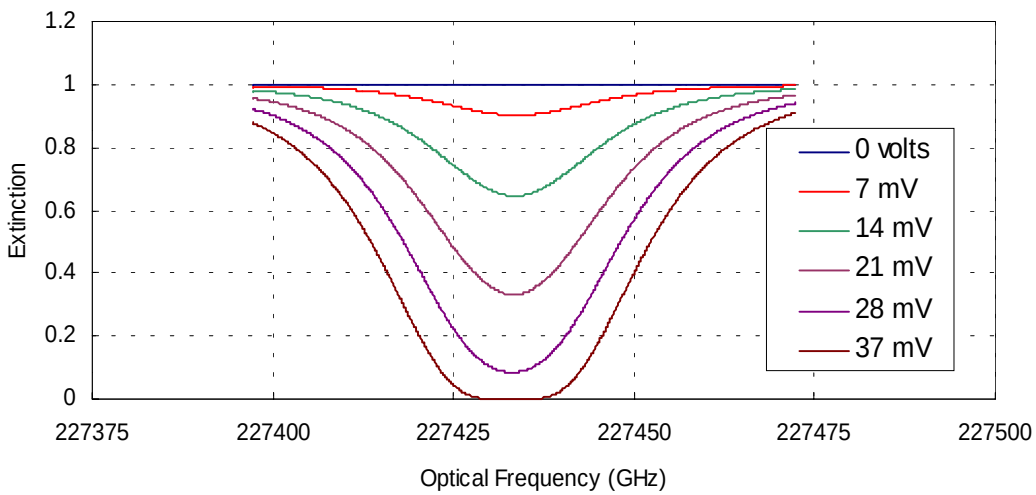
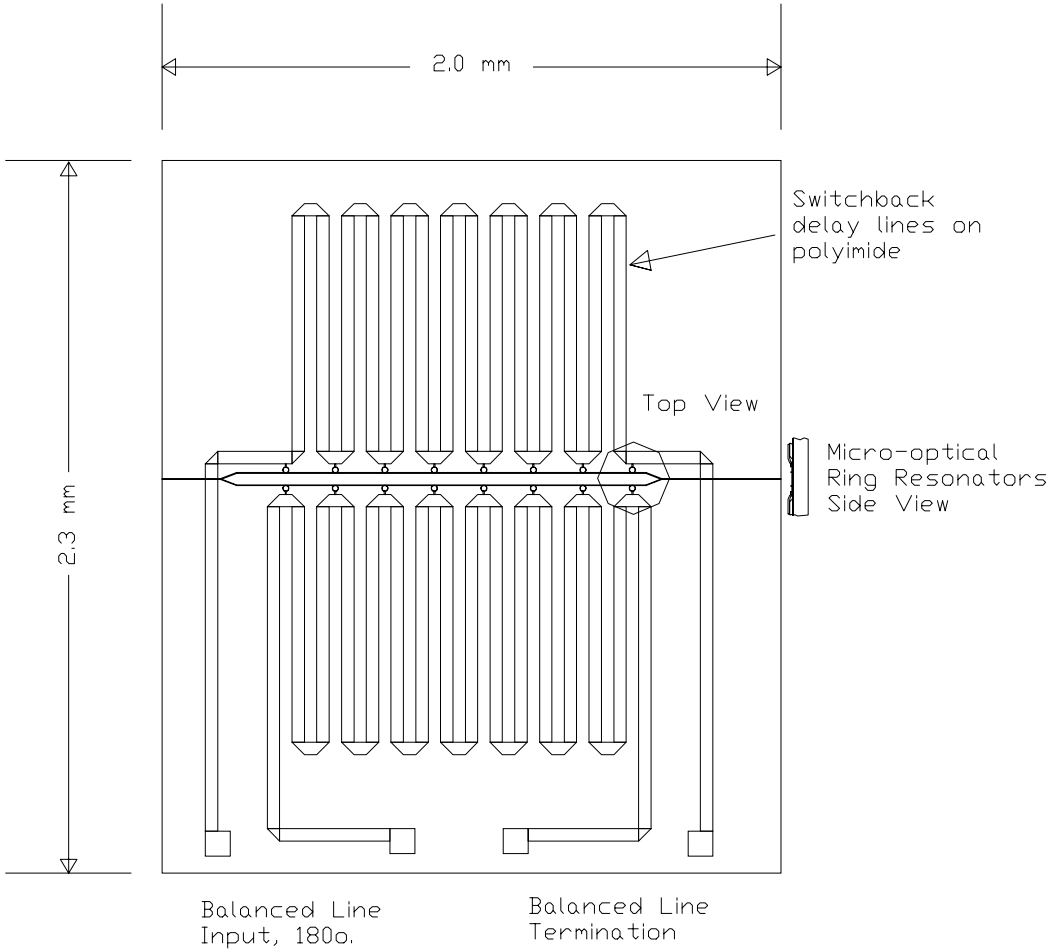
Sixteen-Ring Modulator



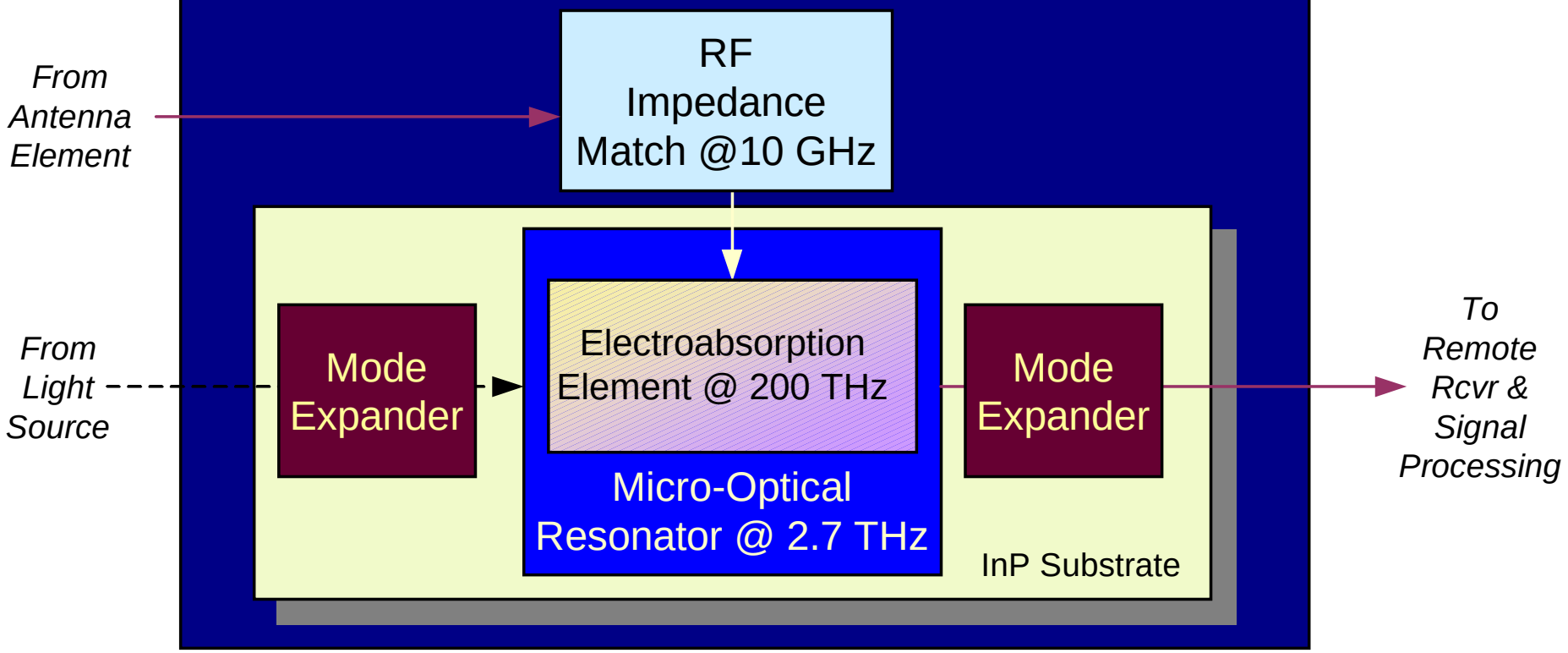


- **Push-Pull Config'n**
- **37 mV = V_π**
- **10 GHz Operation**

RF Delay Line Structure

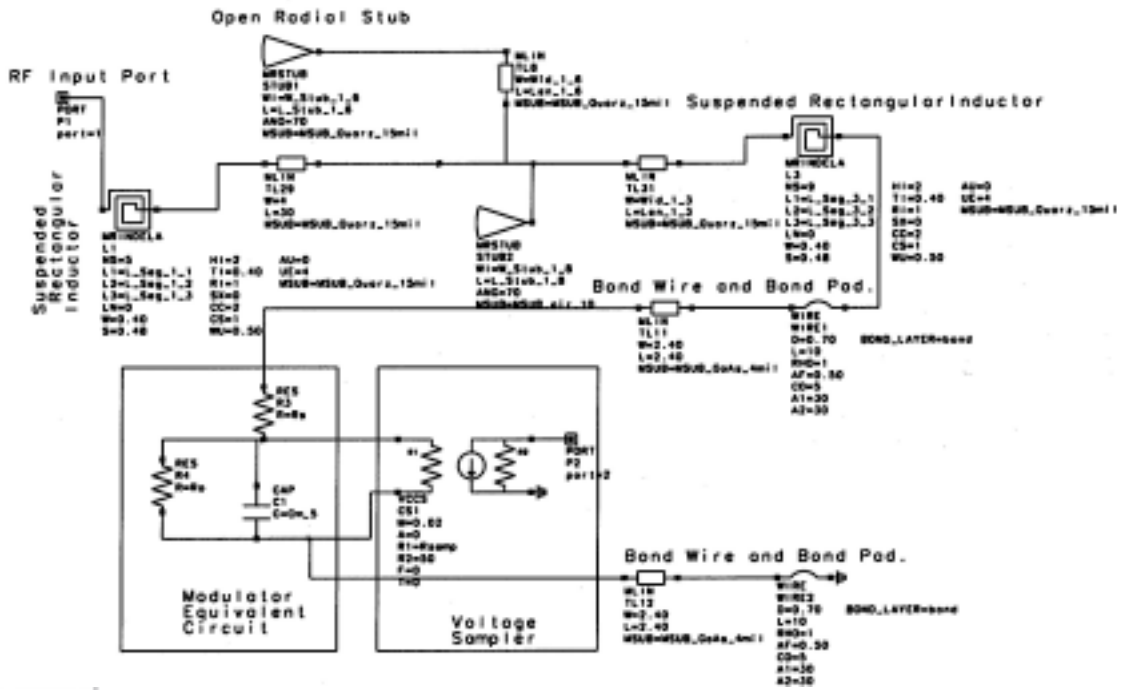


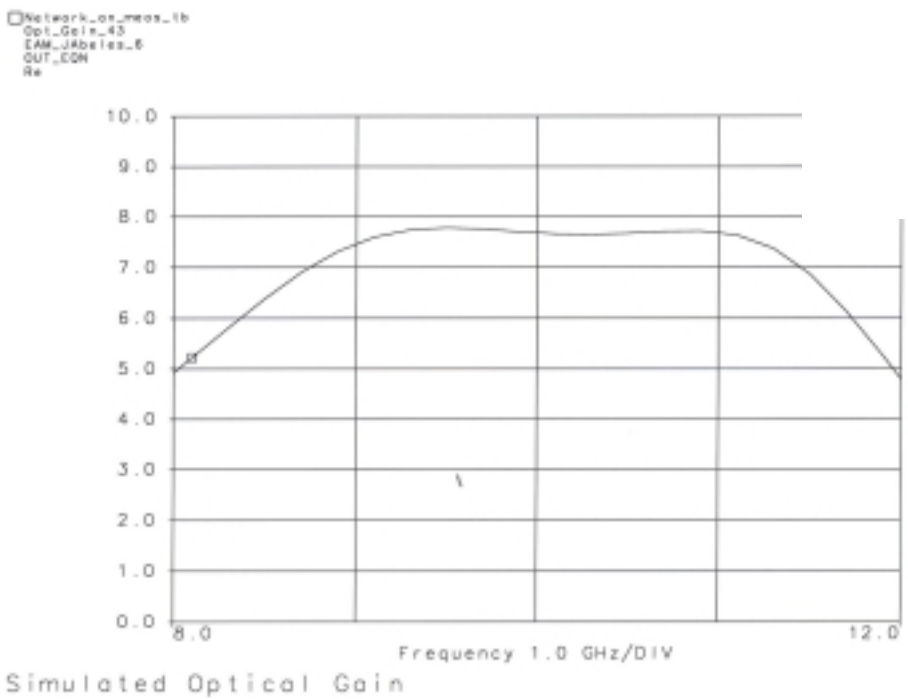
Resonant Enhanced Modulator: Triply Resonant



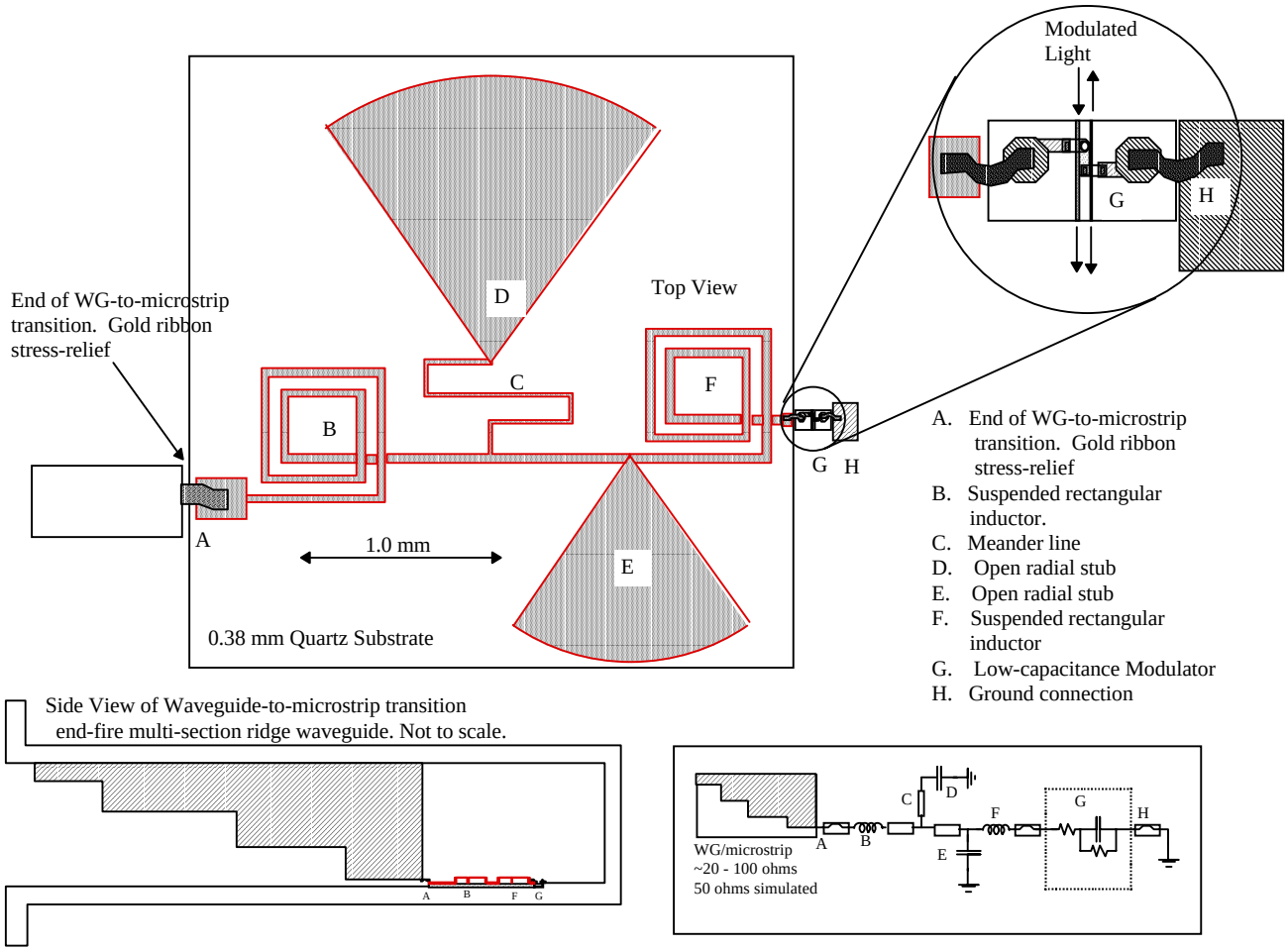
Microwave Impedance Transformer

8 dB Gain



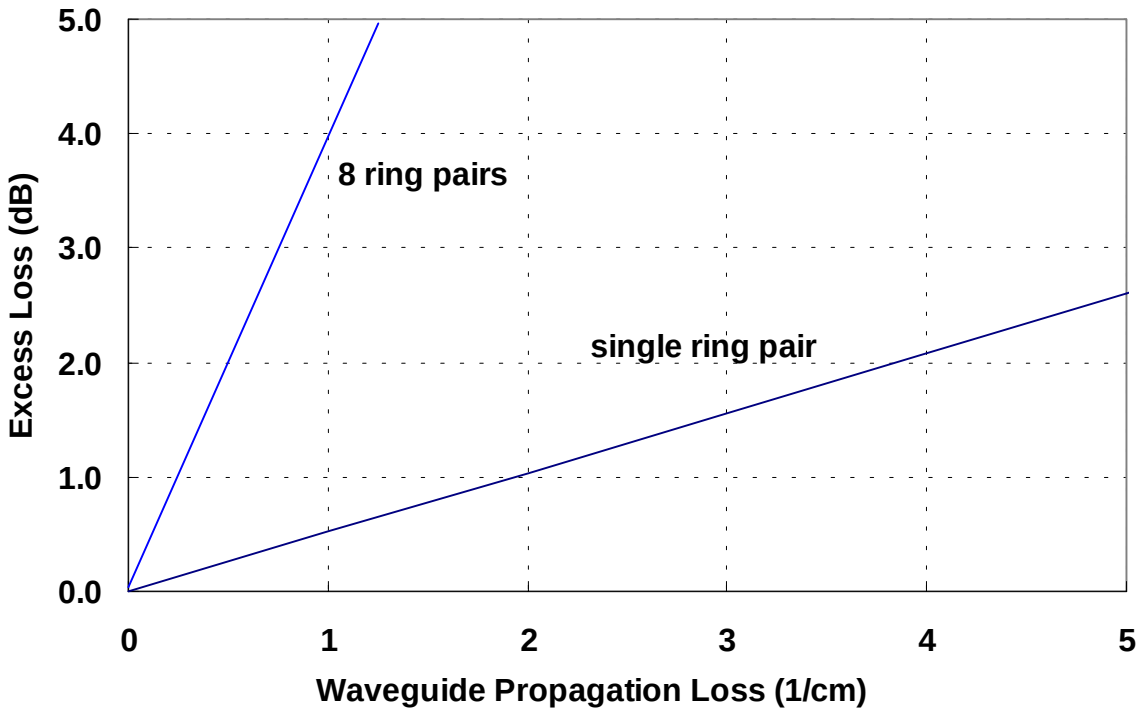


Example Design Layout



Propagation Loss Effects

- **Propagation losses ~ 1 cm^{-1}**
- **Consistent with 3 dB excess loss**



Sarnoff/UIUC Organization & Goals

Sarnoff:

G. Pajer, A. Braun, T.P. Lee
R. Menna, J. Abeles (PI)

UIUC:

S. Rommel, I. Adesida (PI)

Resonant Enhanced Modulator

Sarnoff/CREOL REM

- **Design, Test (J.H. Abeles, Sarnoff)**
- **Nanofab (I. Adesida, U. Illinois)**

KEY GOALS:

• V_π	0.025 V
• RF Frequency	10 GHz
• RF Bandwidth	4 GHz
• Insertion Loss	6 dB