Analogue VLSI Implementations of 2D Nonlinear, Active Cochlea Models

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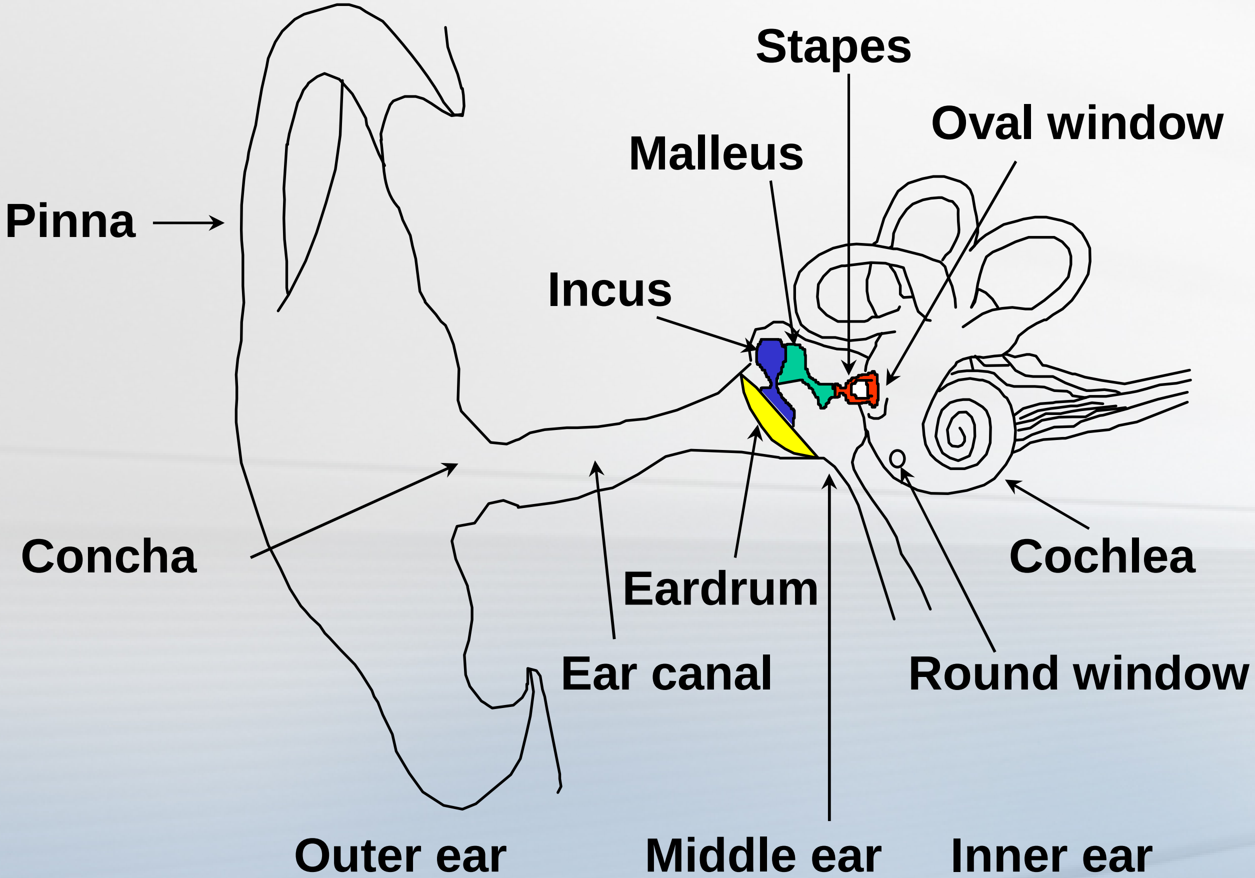
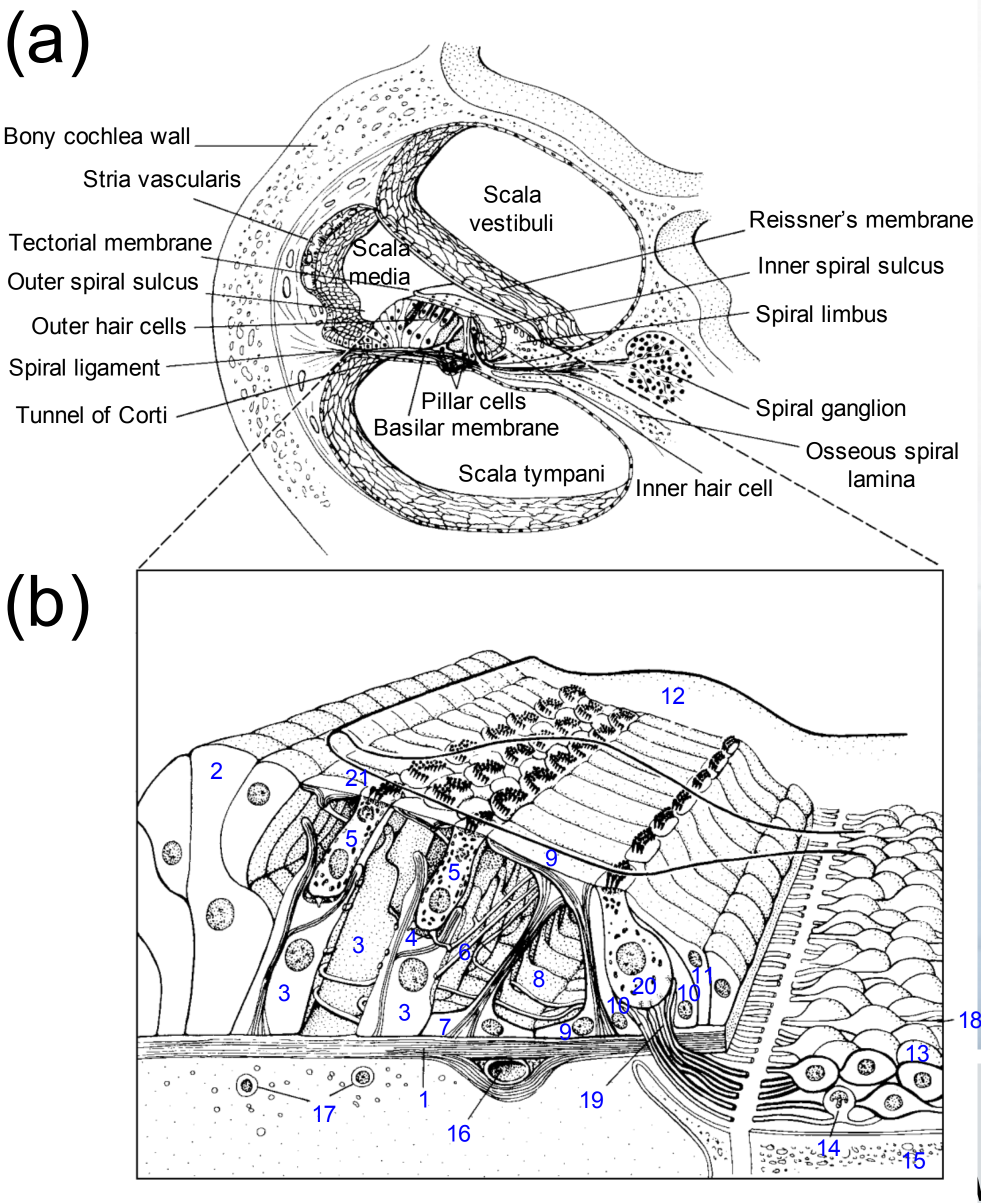
The Telluride Neuromorphic Workshop 2008

The Ear



Stapes
Oval window
Malleus
Pinna
Incus
Concha
Cochlea
Eardrum
Ear canal
Round window
Outer ear
Middle ear
Inner ear

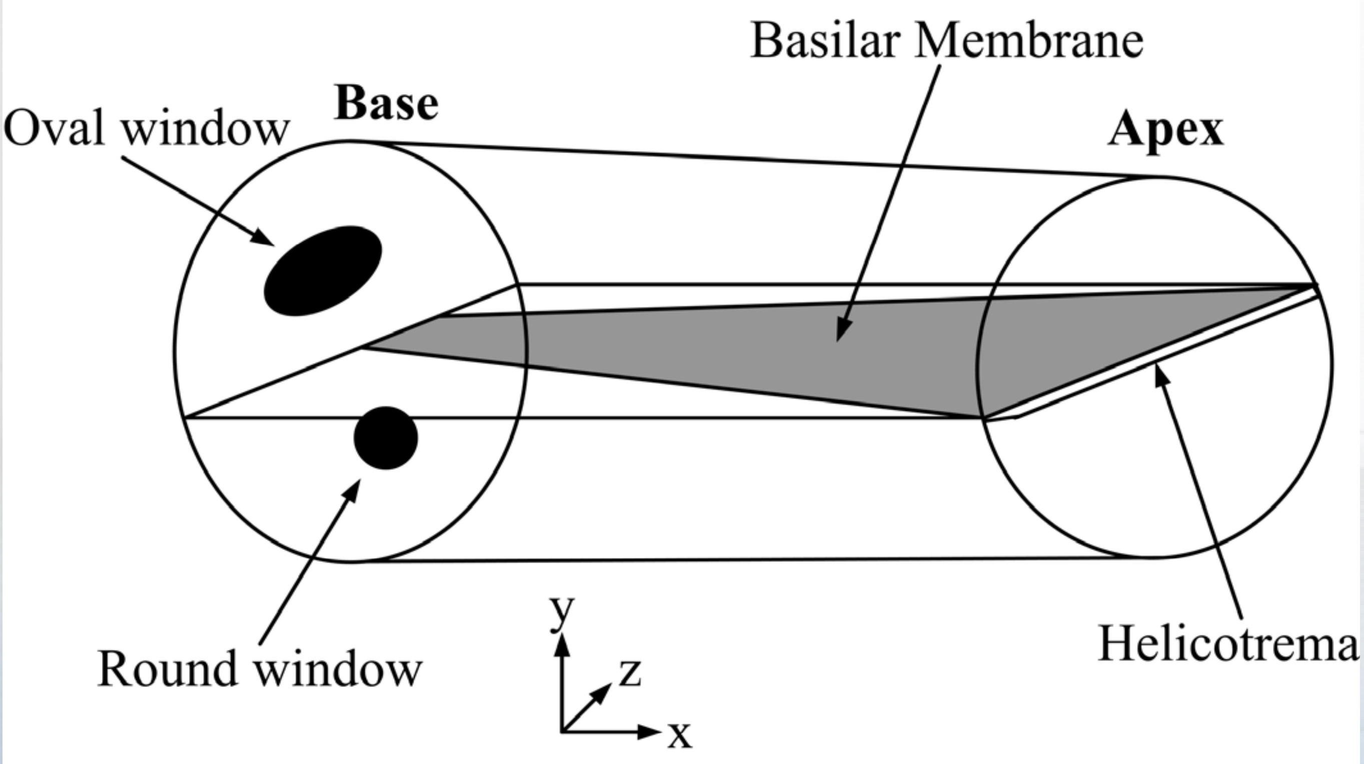
The Cochlea



Workshop 2008

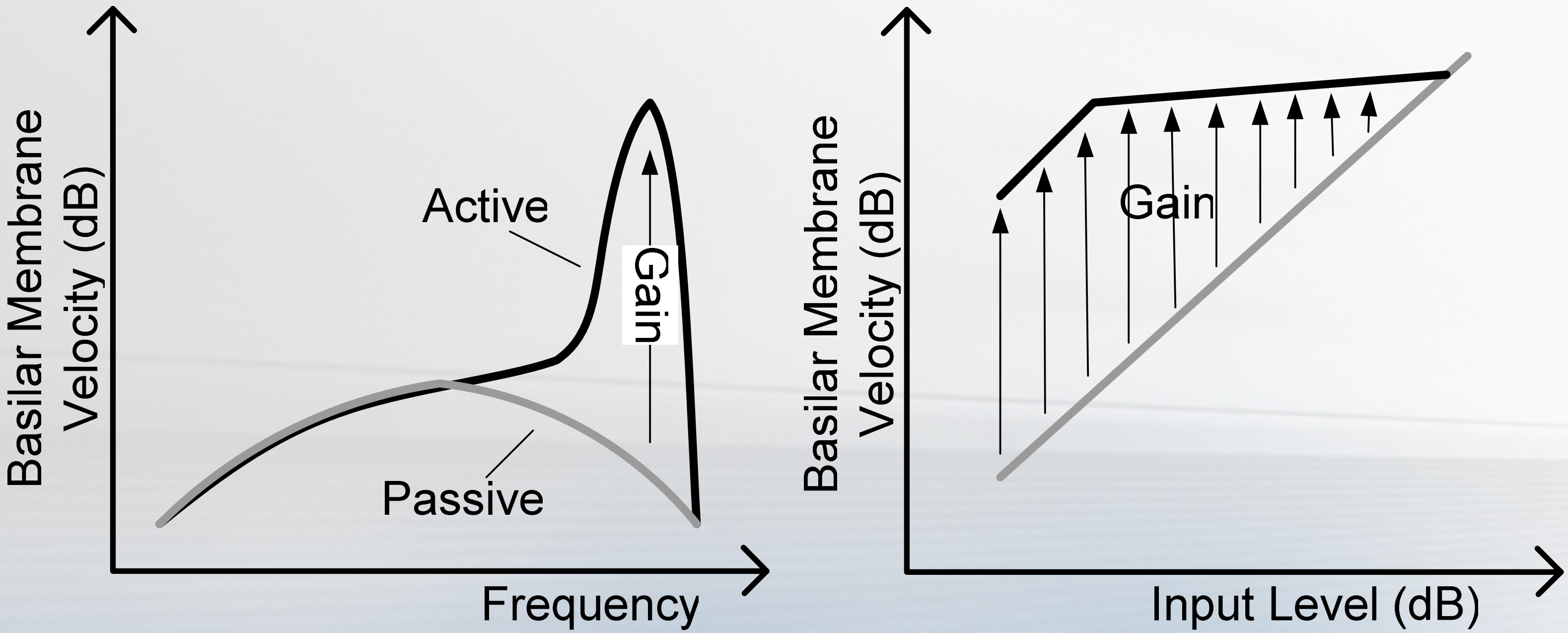
The Cochlea

Uncoiled…



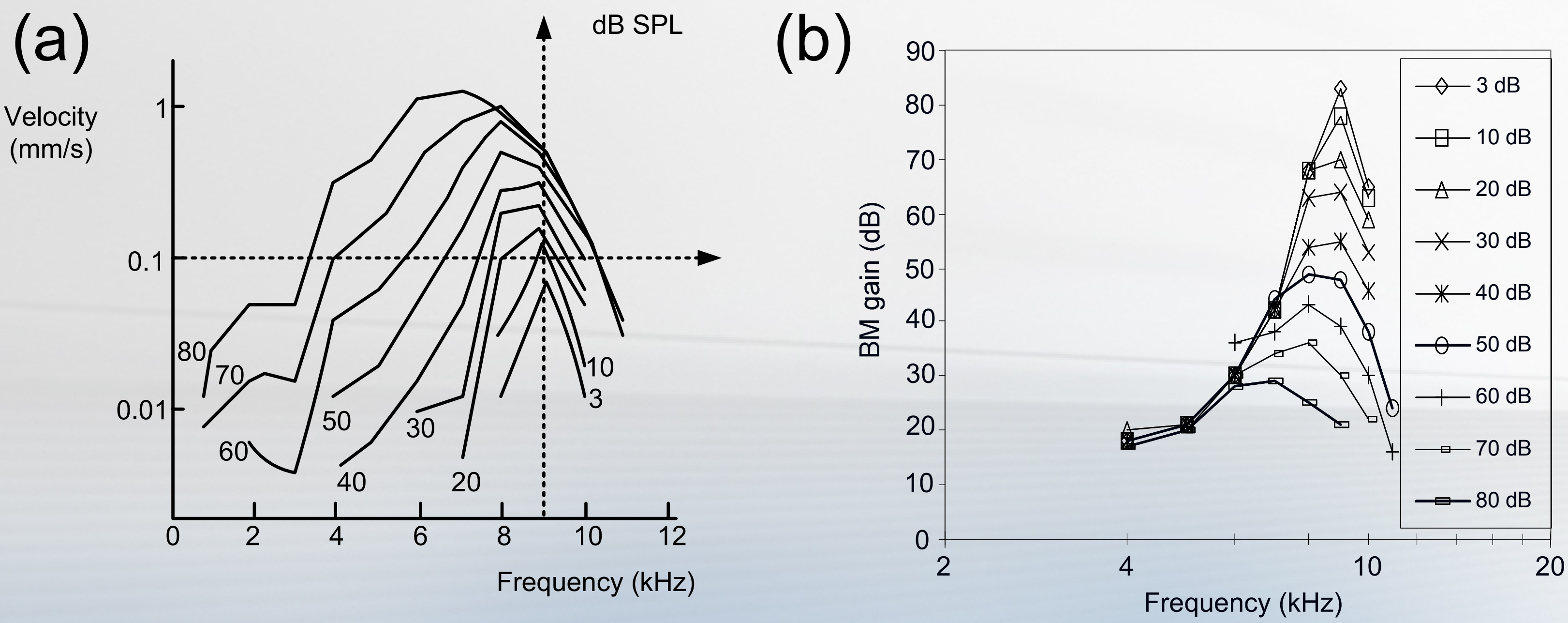
The Cochlea

Active Properties



The Cochlea

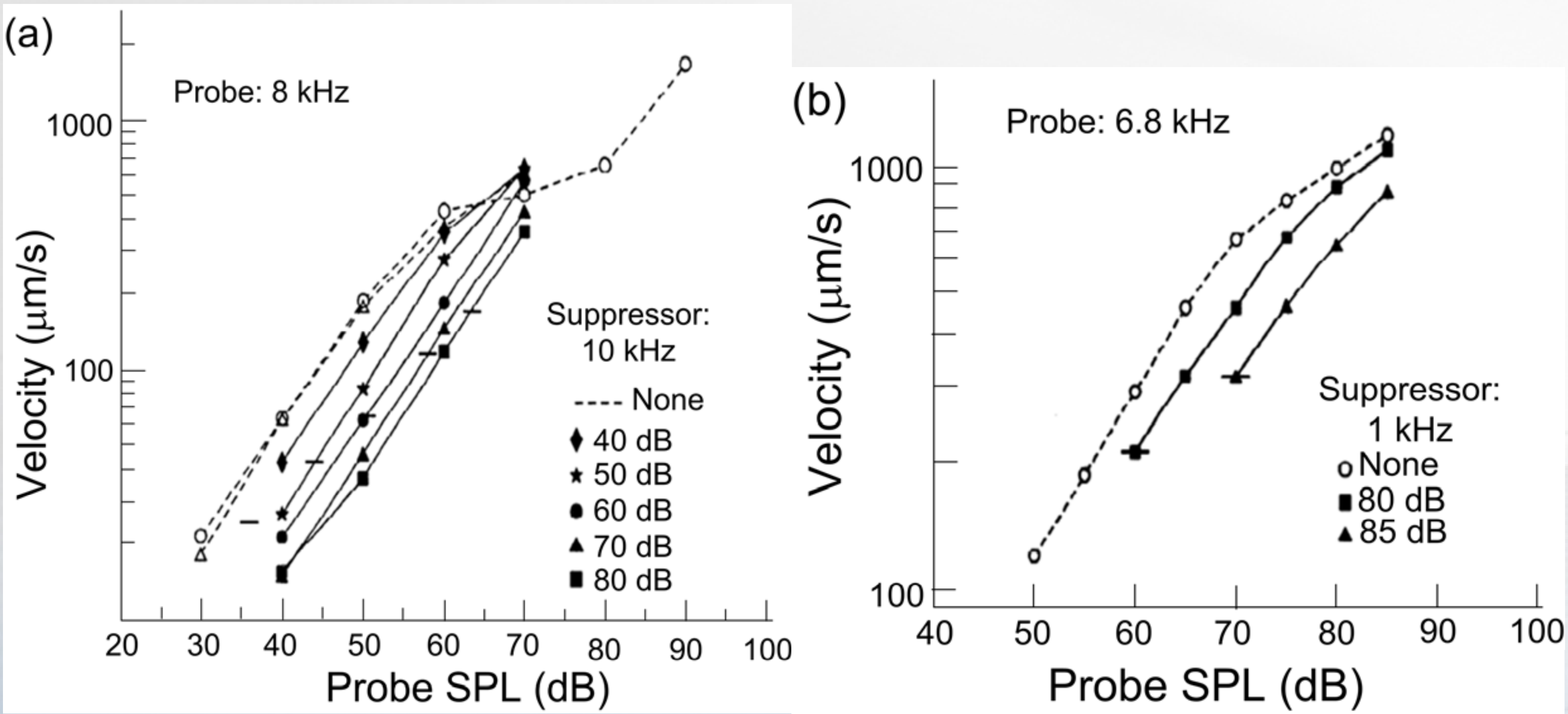
Characteristics – large signal compression



The Chinchilla

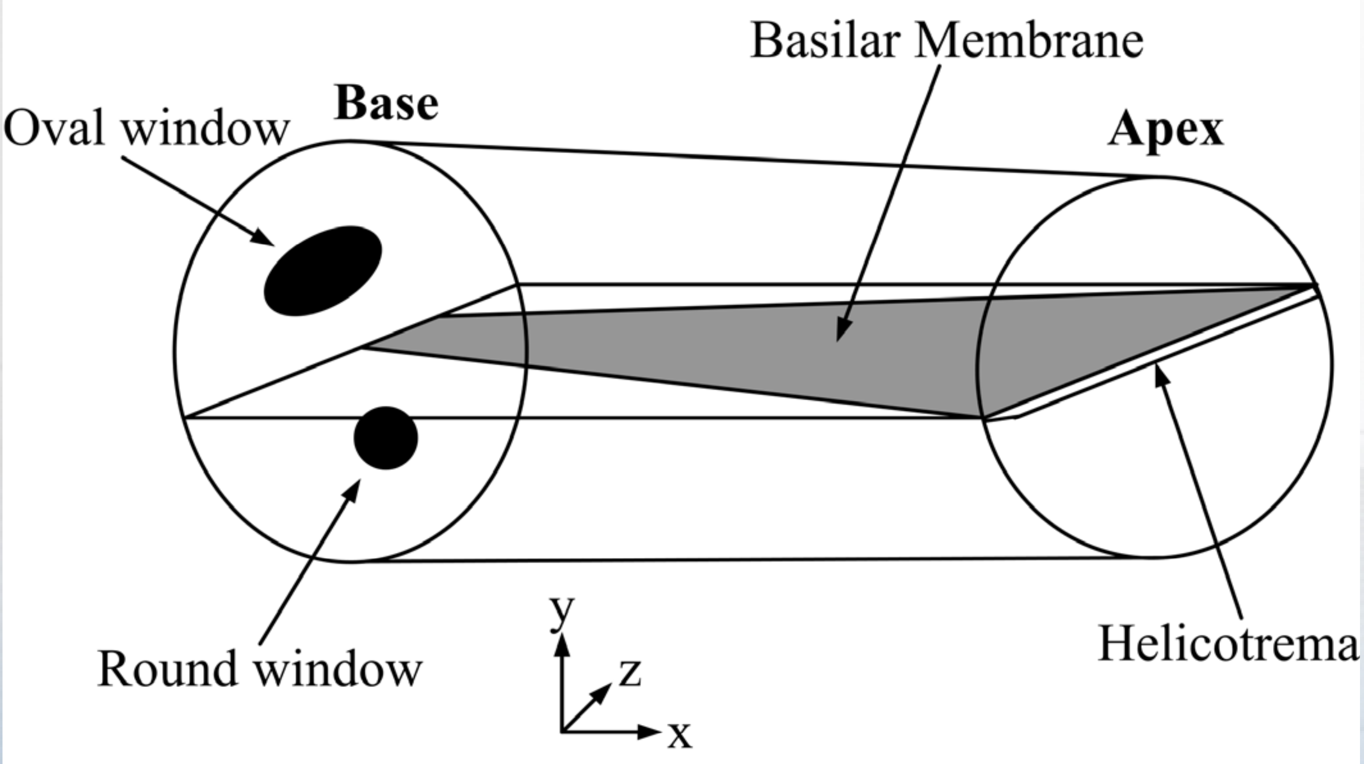
The Cochlea

Characteristics – two-tone suppression



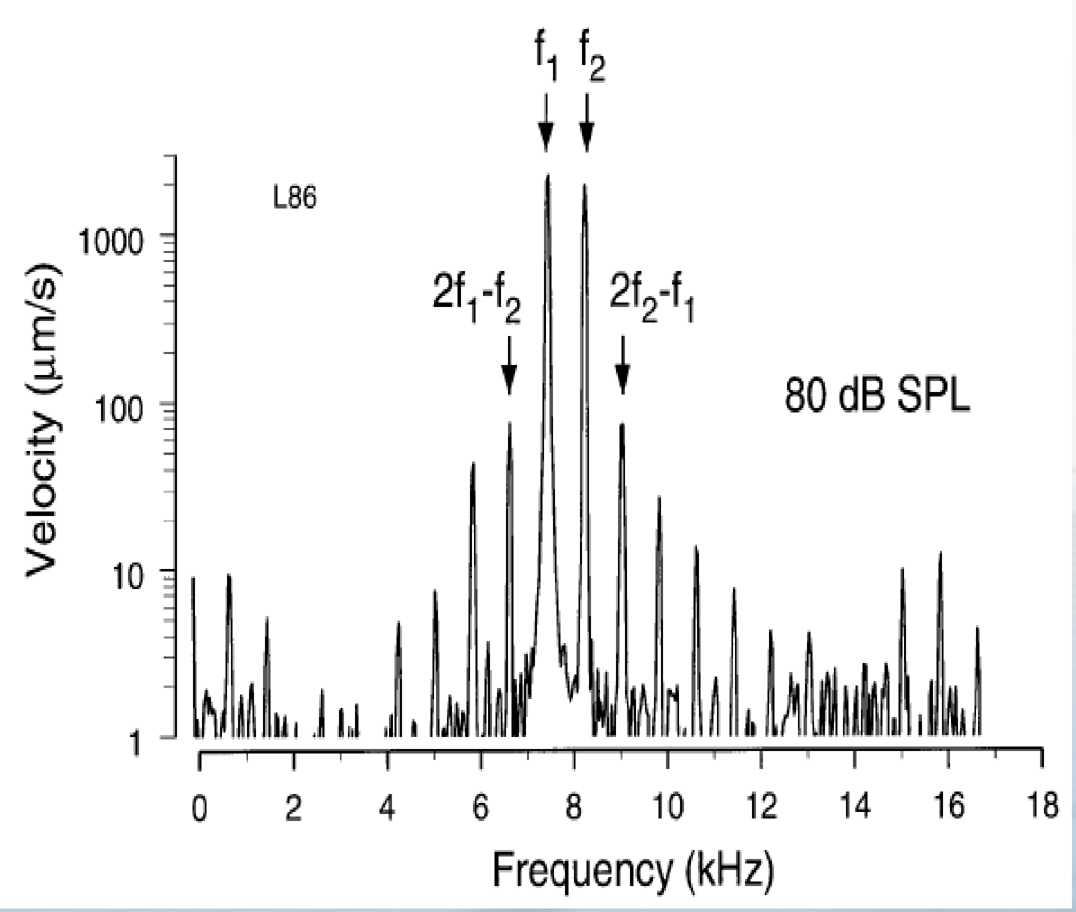
The Cochlea

Uncoiled…



The Cochlea

Characteristics – combinational tones

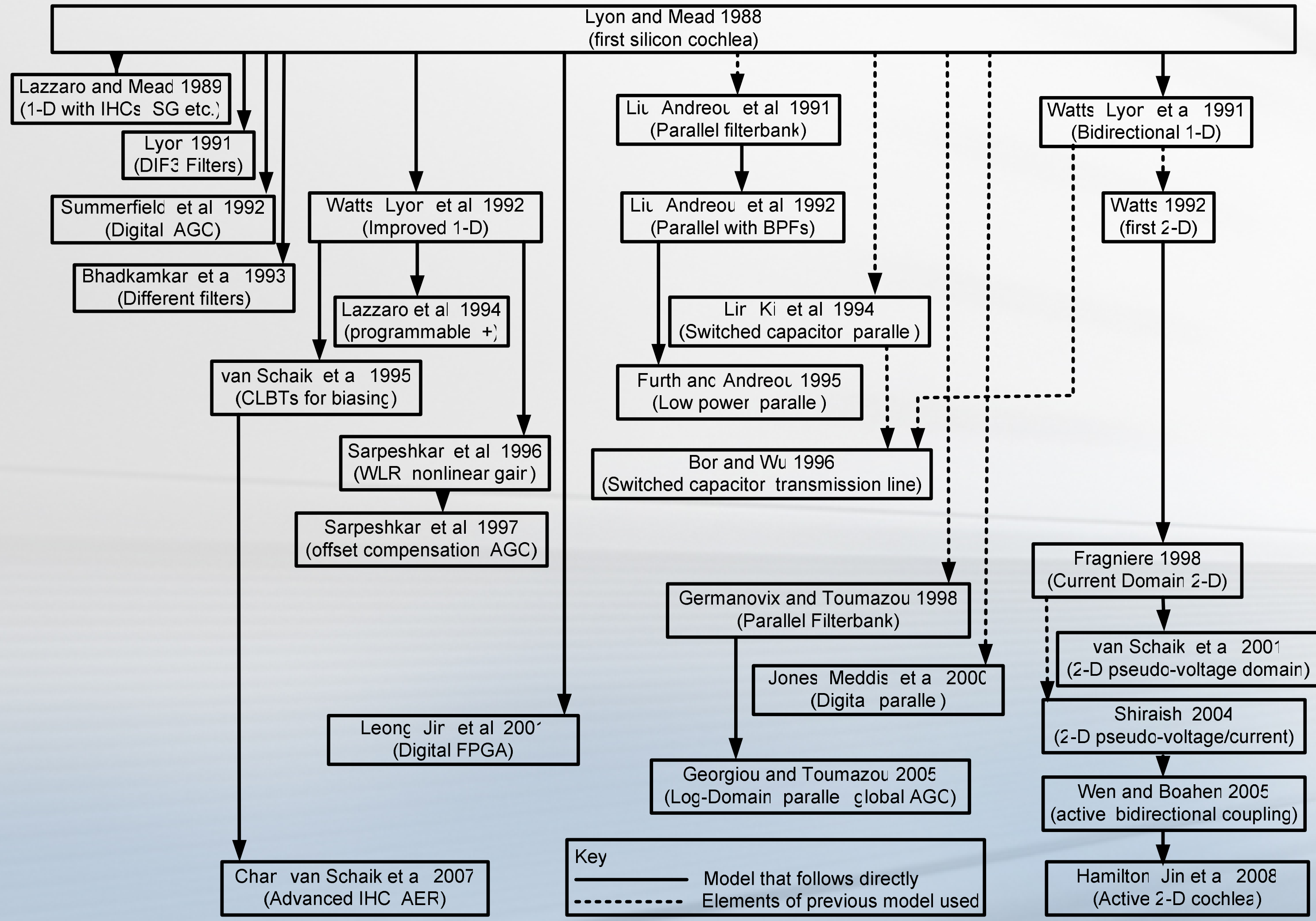


Silicon Cochlea

Why???

- Real-time
- Noise and Mismatch
- Building block
- Hearing Devices

Silicon Cochleae



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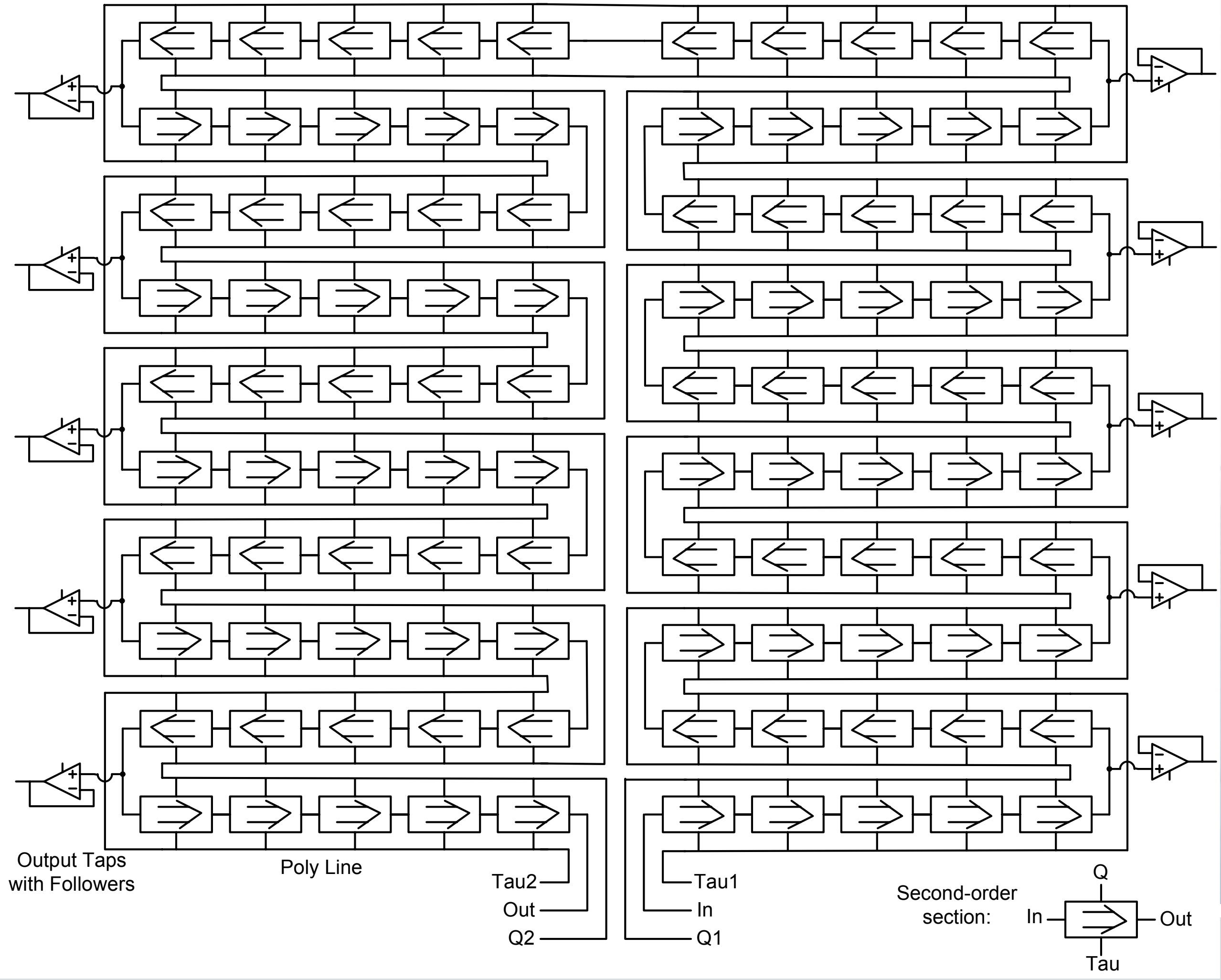
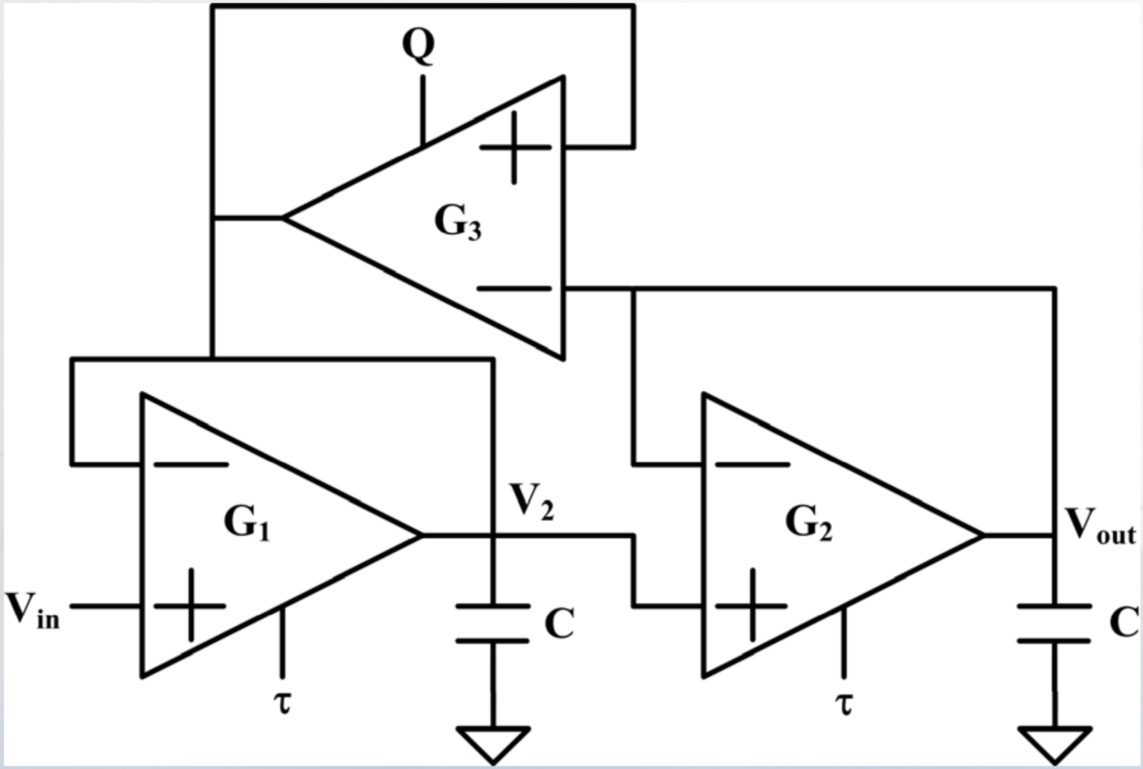
Silicon Cochleae

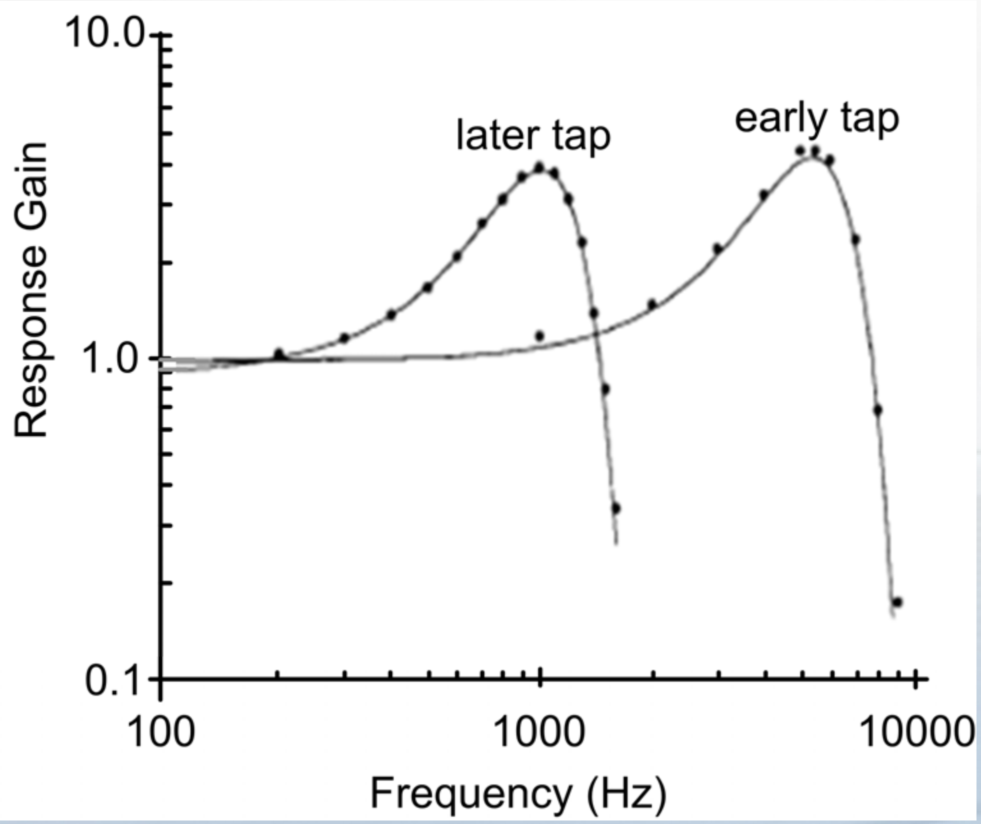
Lyon and Mead 1988



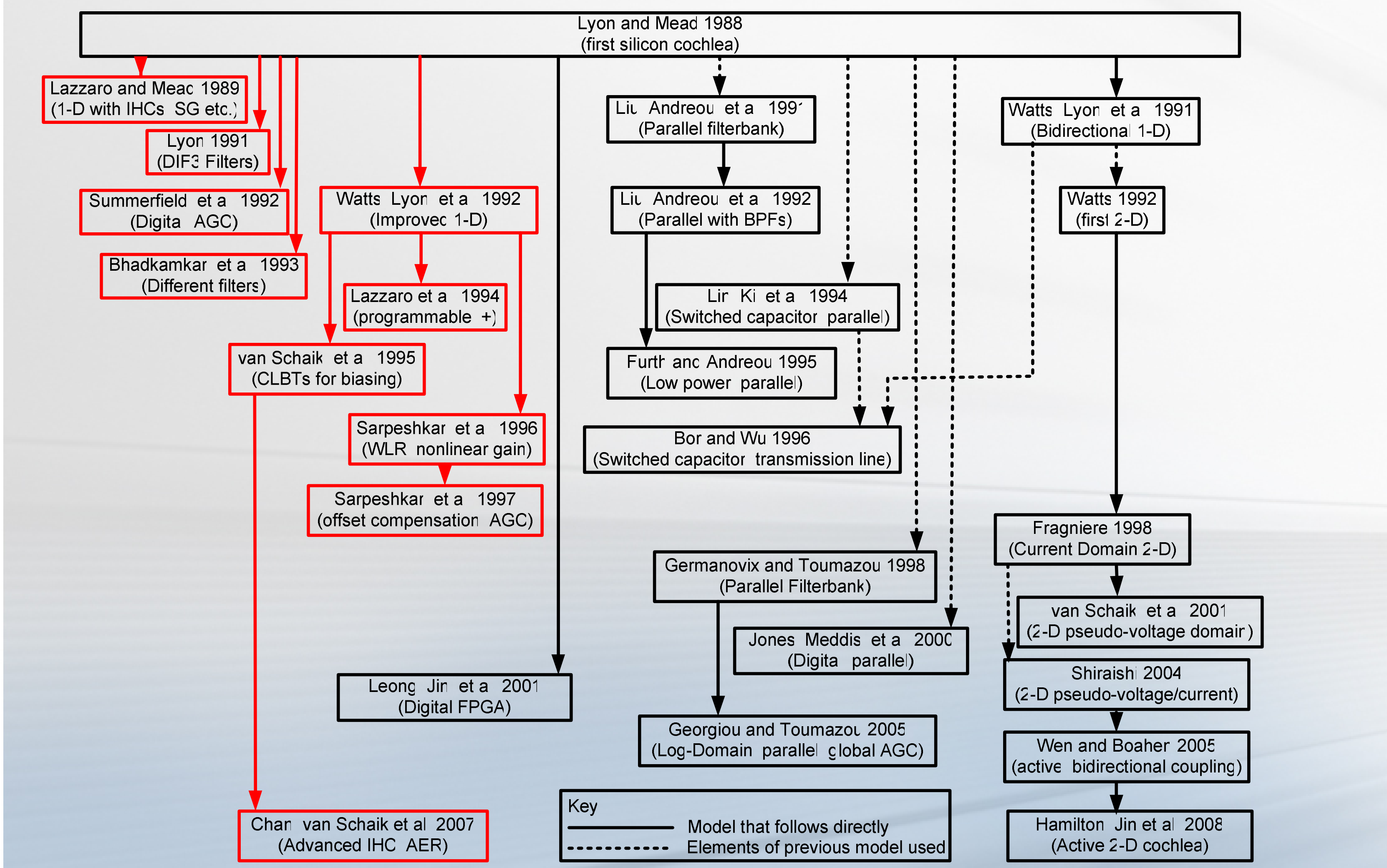
Silicon Cochleae



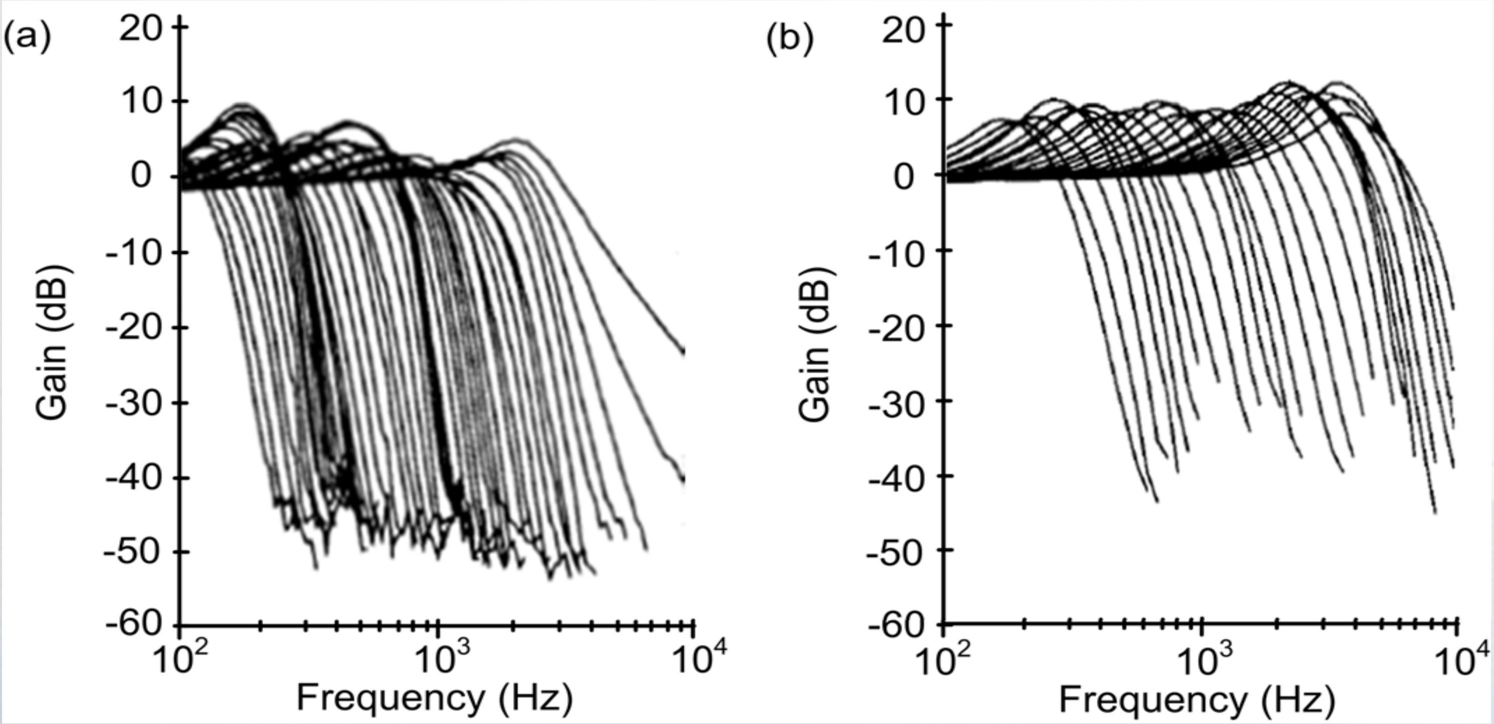
Silicon Cochleae



Silicon Cochleae

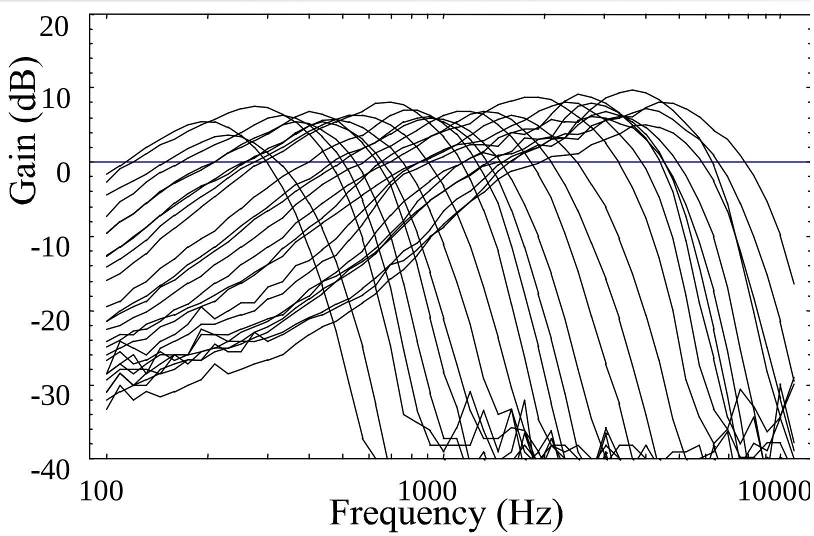


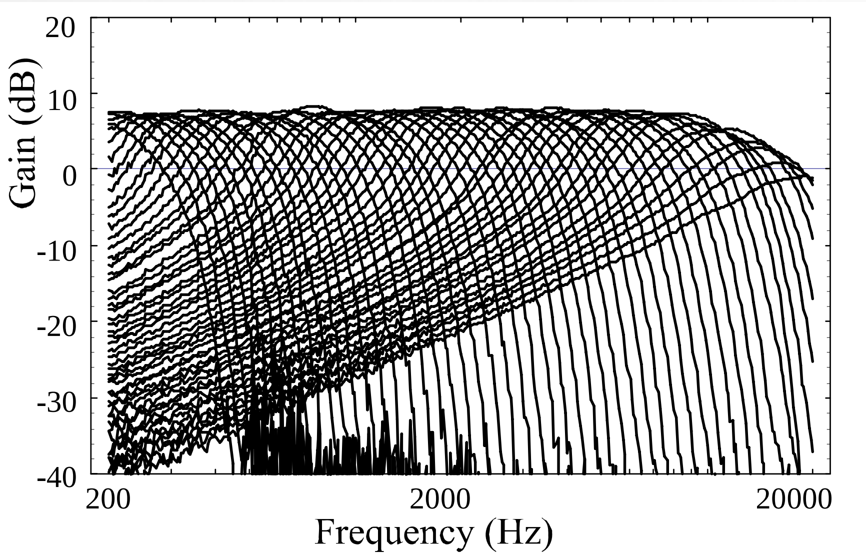
Silicon Cochleae



Watts, Kerns, et al. 1992

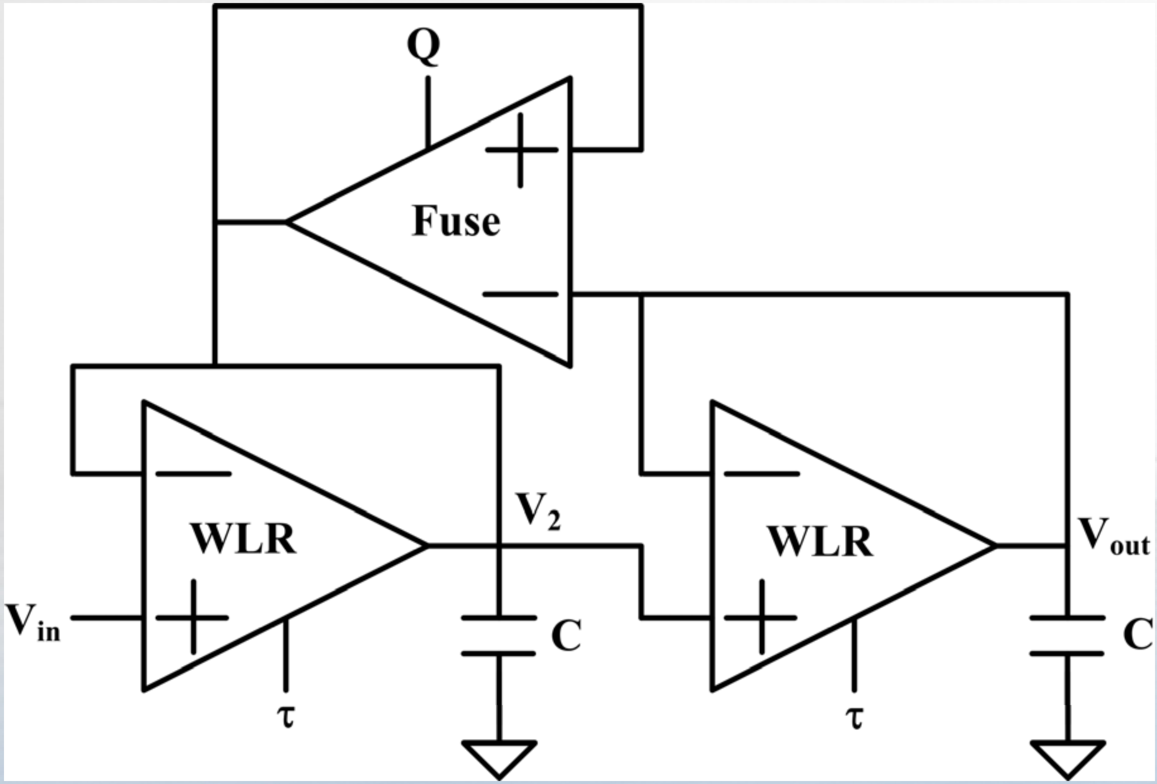
Silicon Cochleae





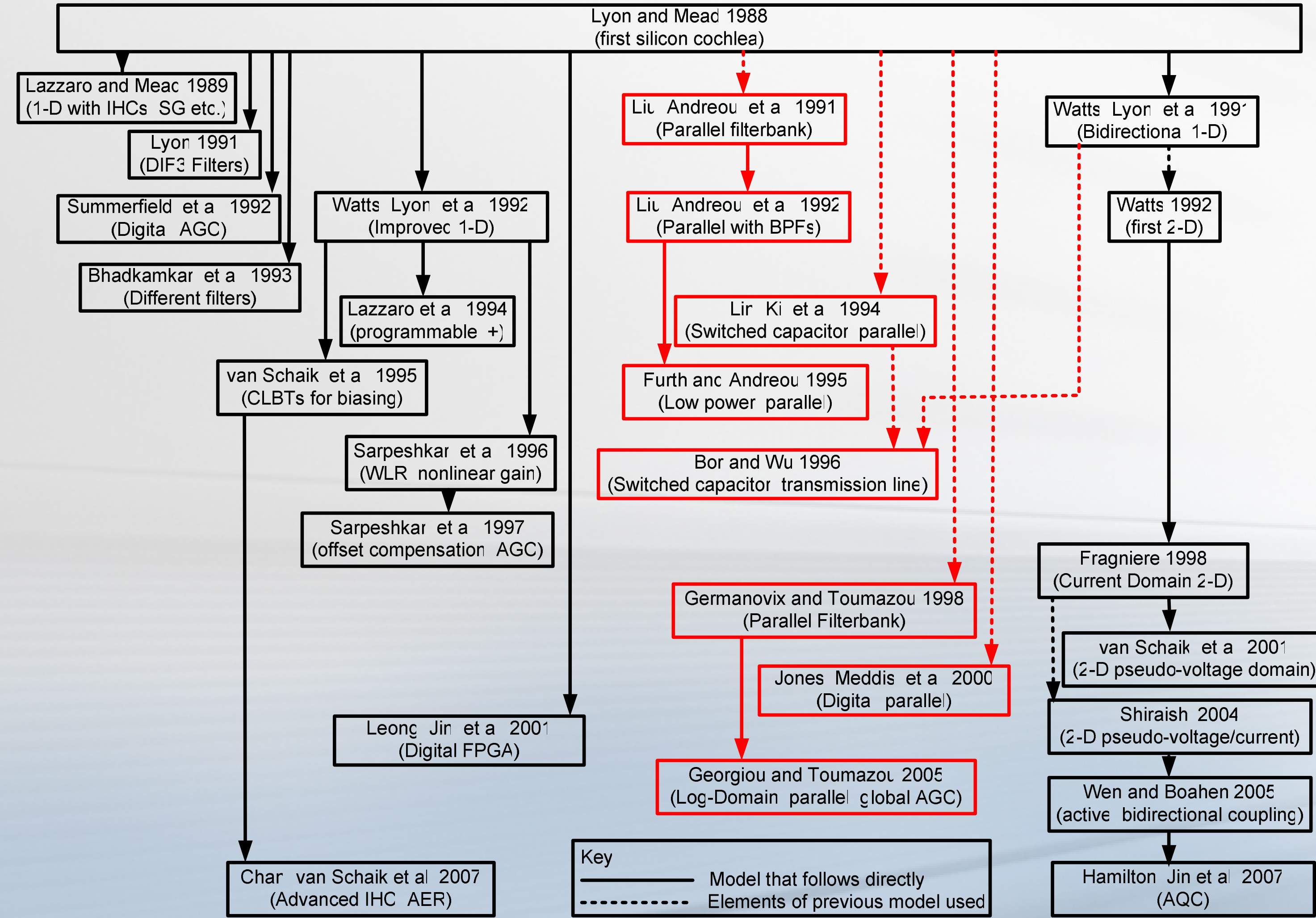
van Schaik, Fragniere et al. 1995

Silicon Cochleae



Sarpeshkar, Lyon et al. 1998

Silicon Cochleae



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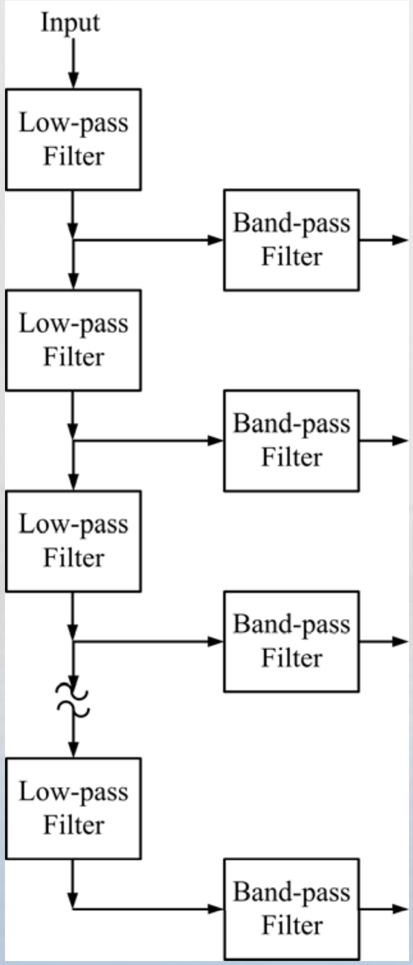
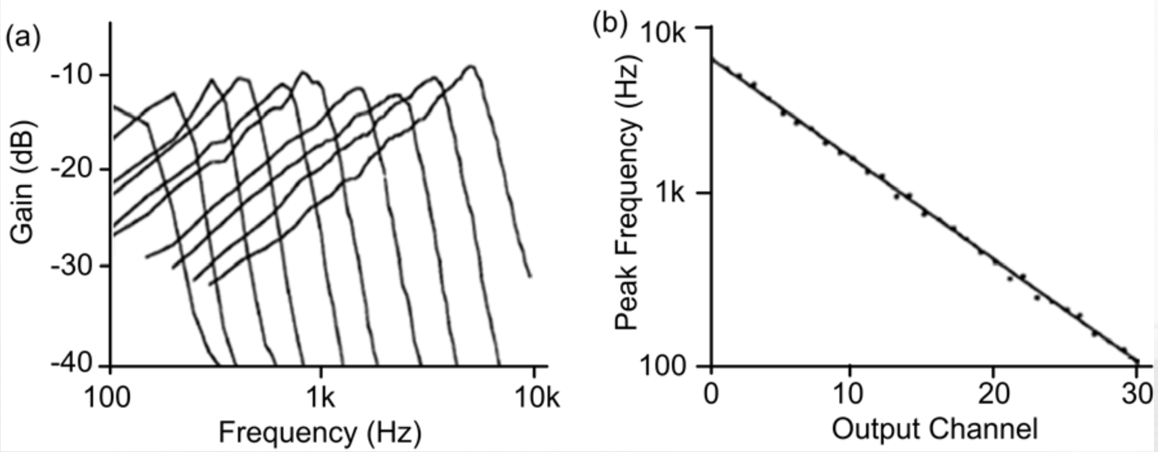
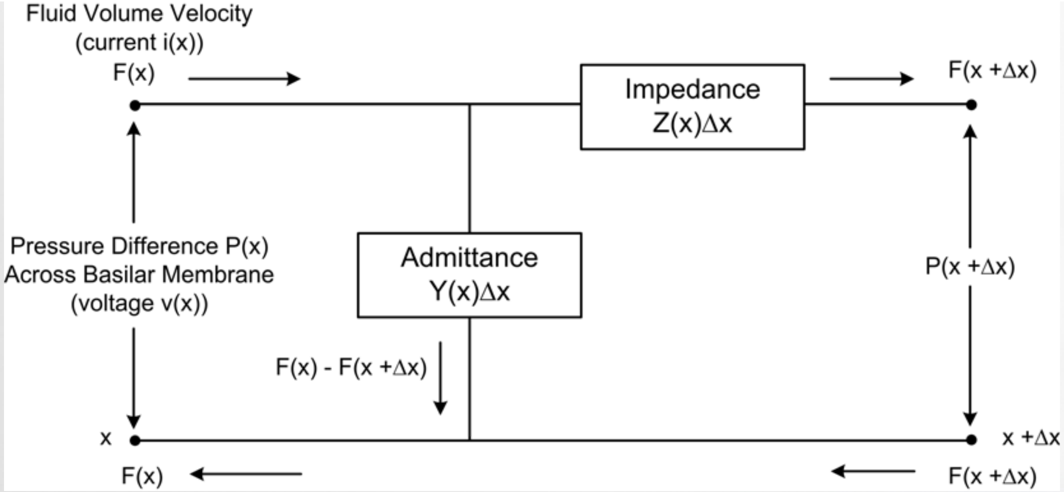
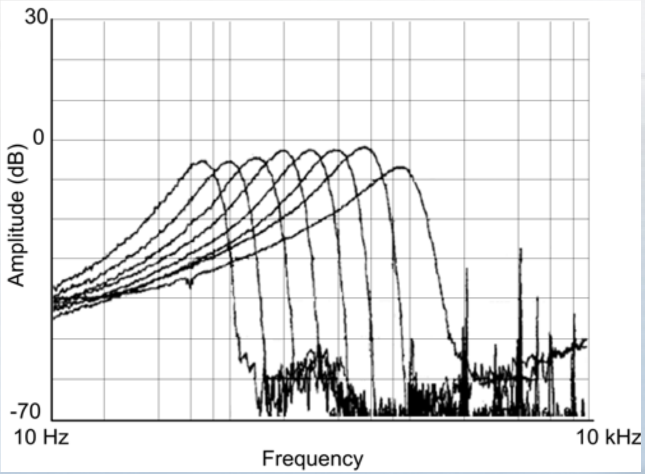




Liu, Andreou et al. 1992

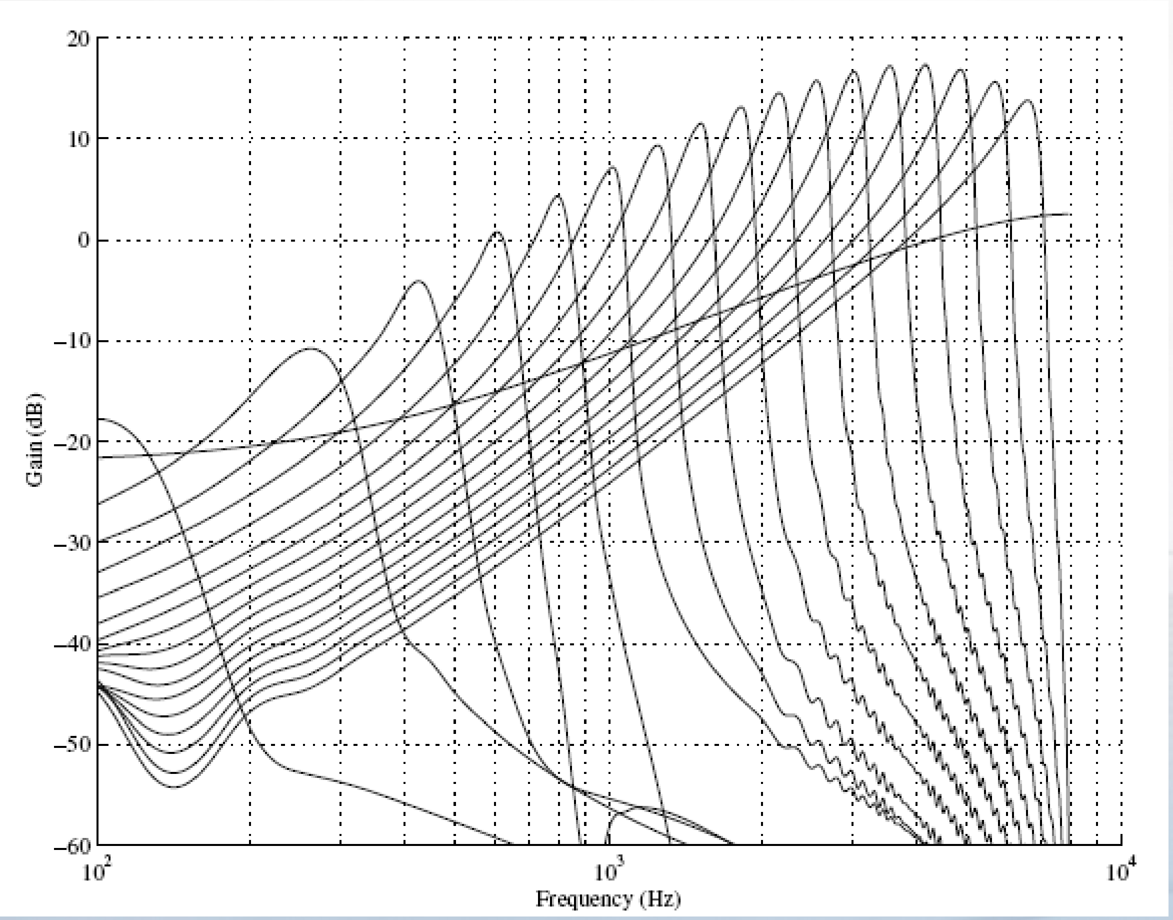
Silicon Cochleae





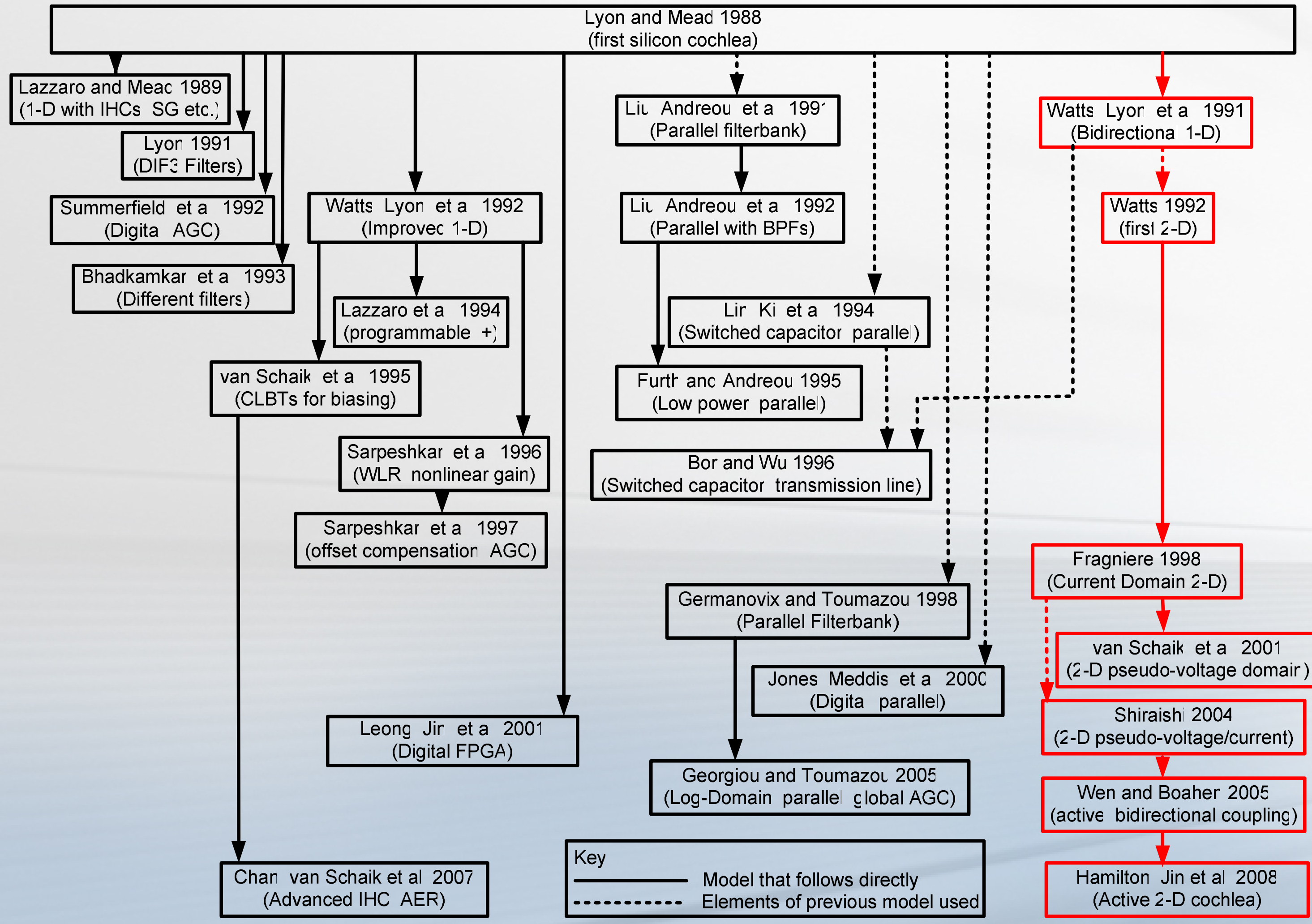
Jenn-Chyou and Chung-Yu 1996

Silicon Cochleae



Leong, Jin et al. 2001

Silicon Cochleae



Silicon Cochleae

Velocity potential in an incompressible and inviscid fluid:

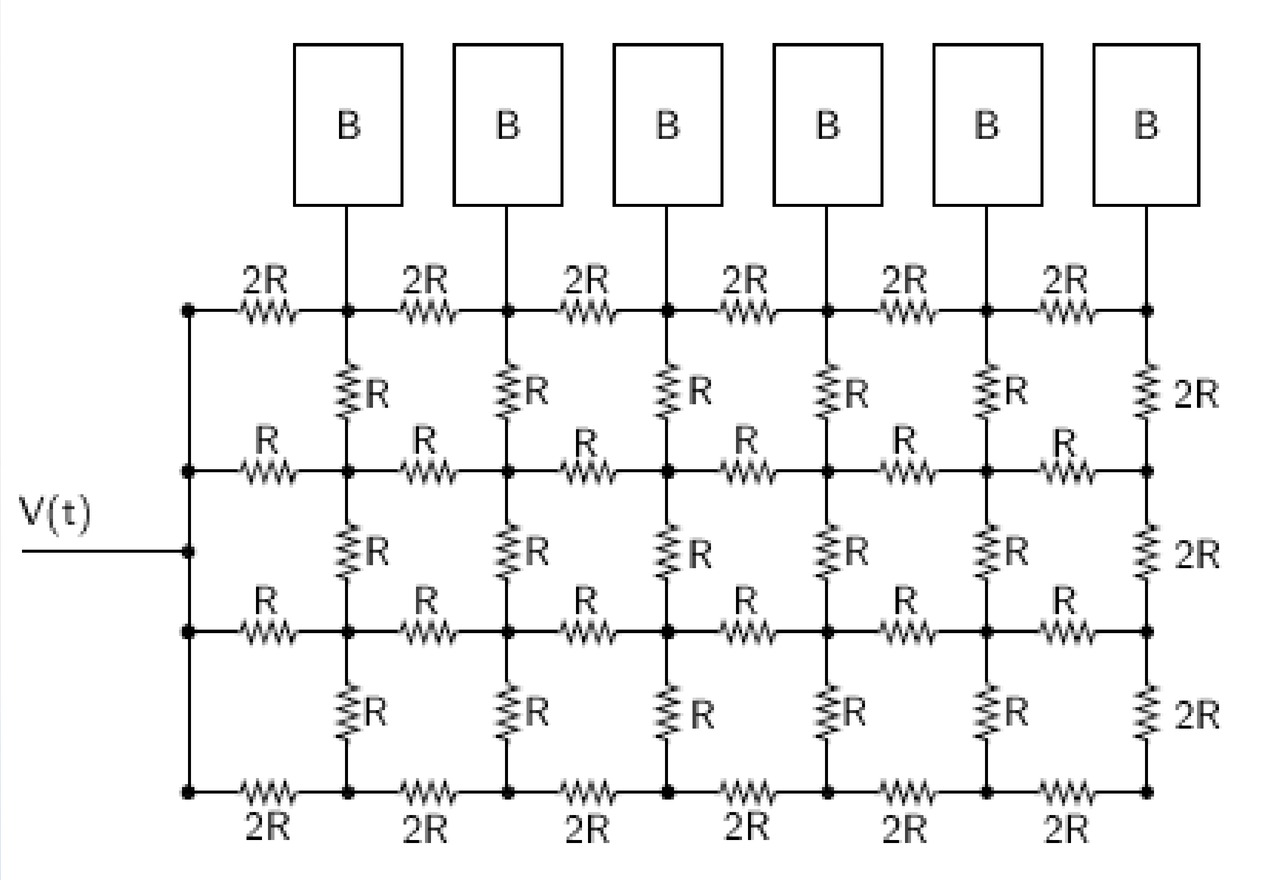
$$-2\rho\frac{\partial^2\phi}{\partial t^2}=S(x)\frac{\partial\phi}{\partial t}+\beta(x)\frac{\partial^2\phi}{\partial y\partial t}+M(x)\frac{\partial^3\phi}{\partial y\partial t^2}$$

Voltage in a resistive network:

$$\frac{V(x)}{I(x)}dx=\frac{S(x)}{s^2}dx+\frac{\beta(x)}{s}dx+M(x)dx=Z_m(x)dx$$

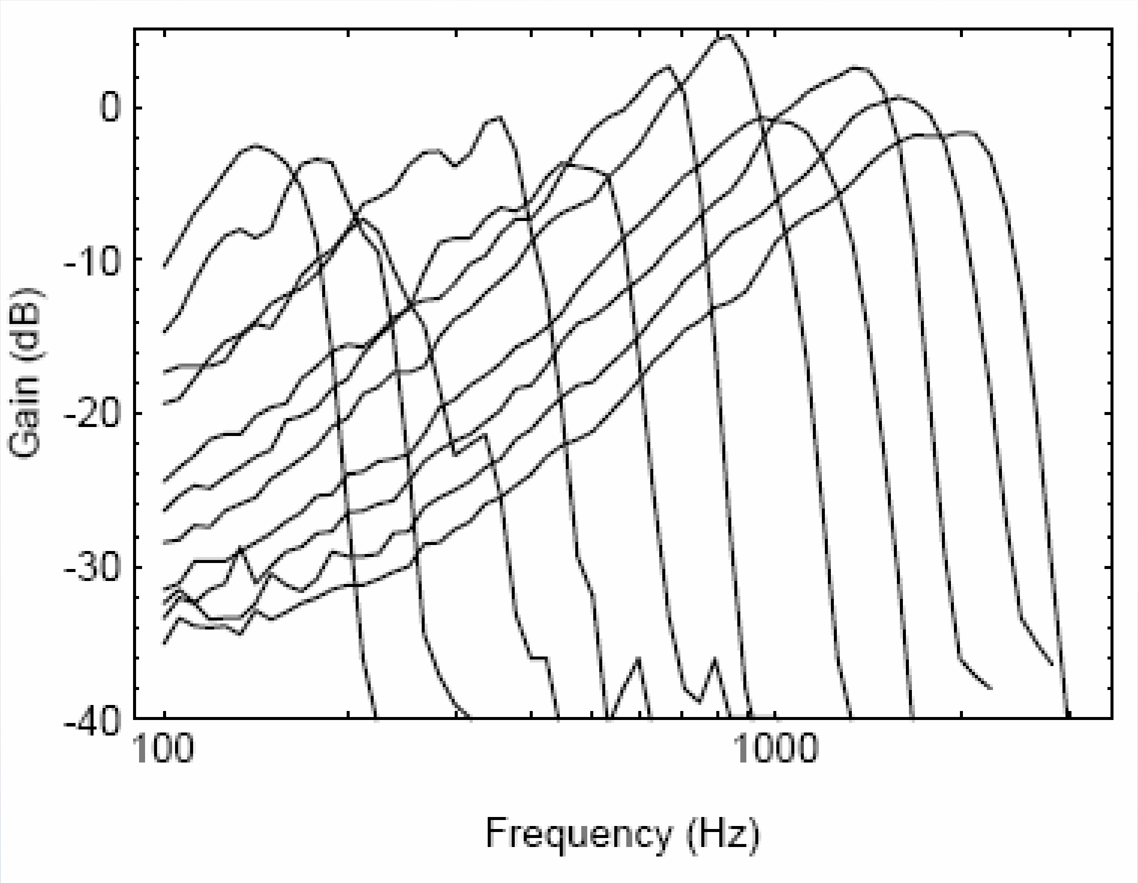
Watts 1992

Silicon Cochleae



Watts 1992

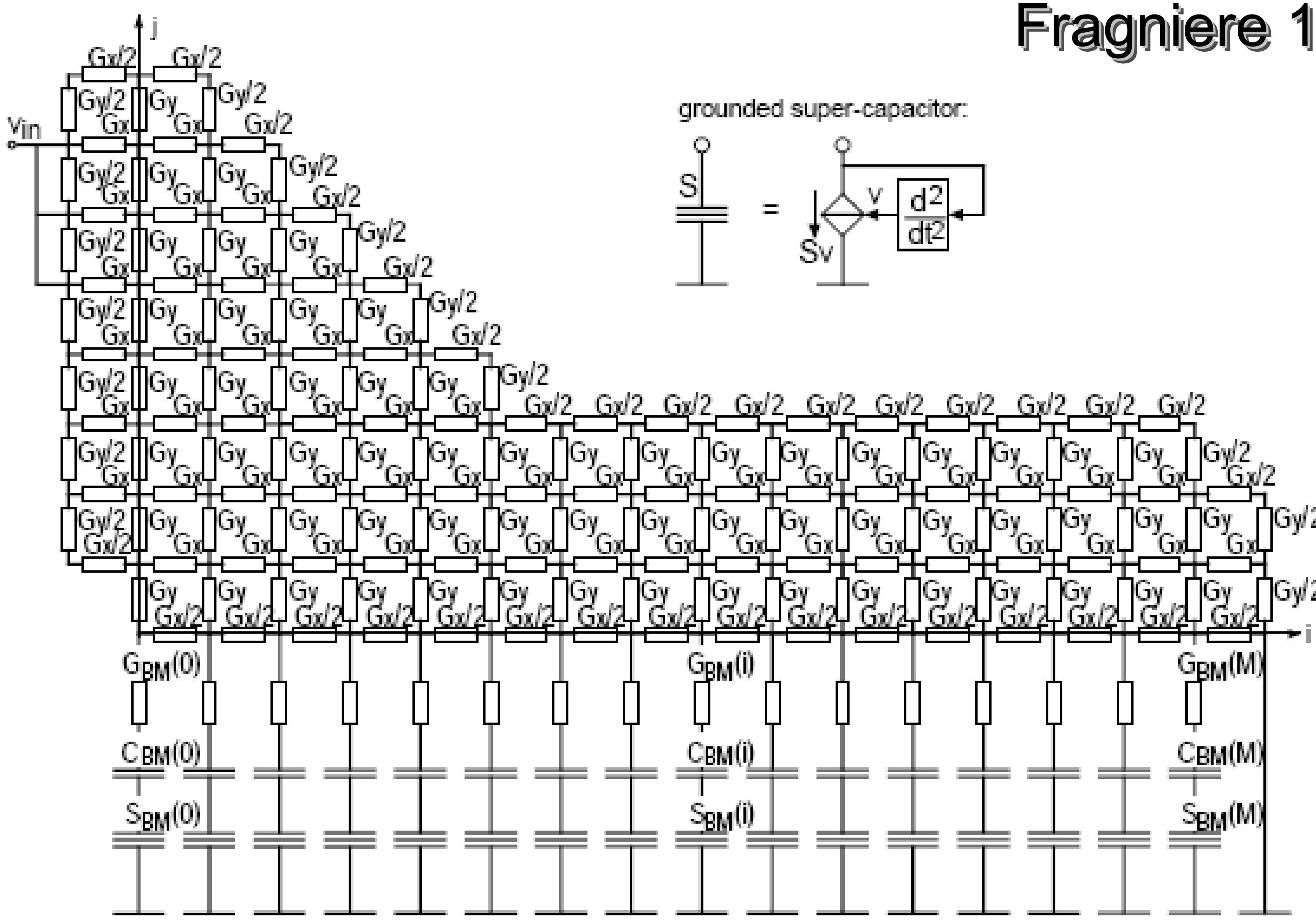
Silicon Cochleae



Watts 1992

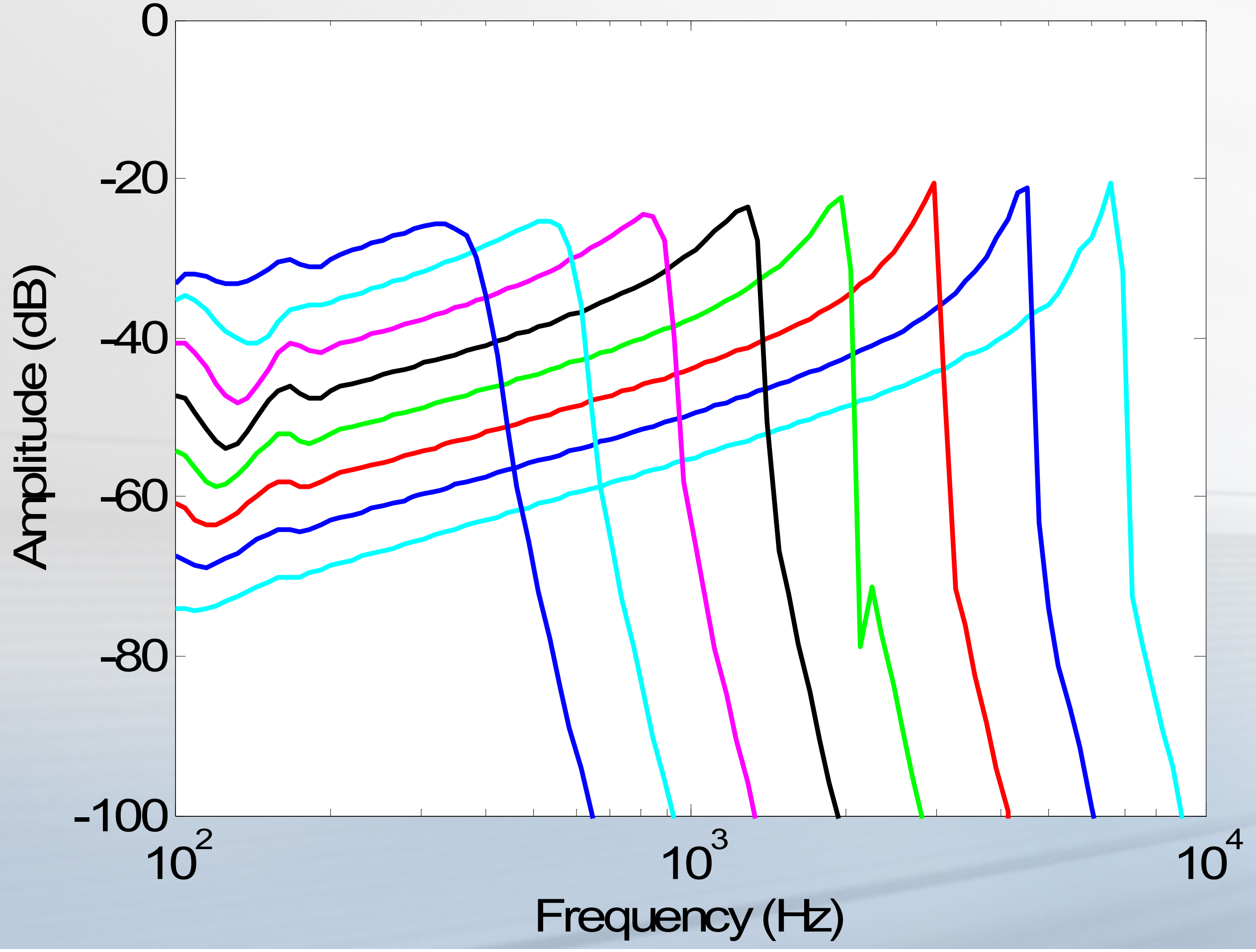
Silicon Cochleae

Fragniere 1998

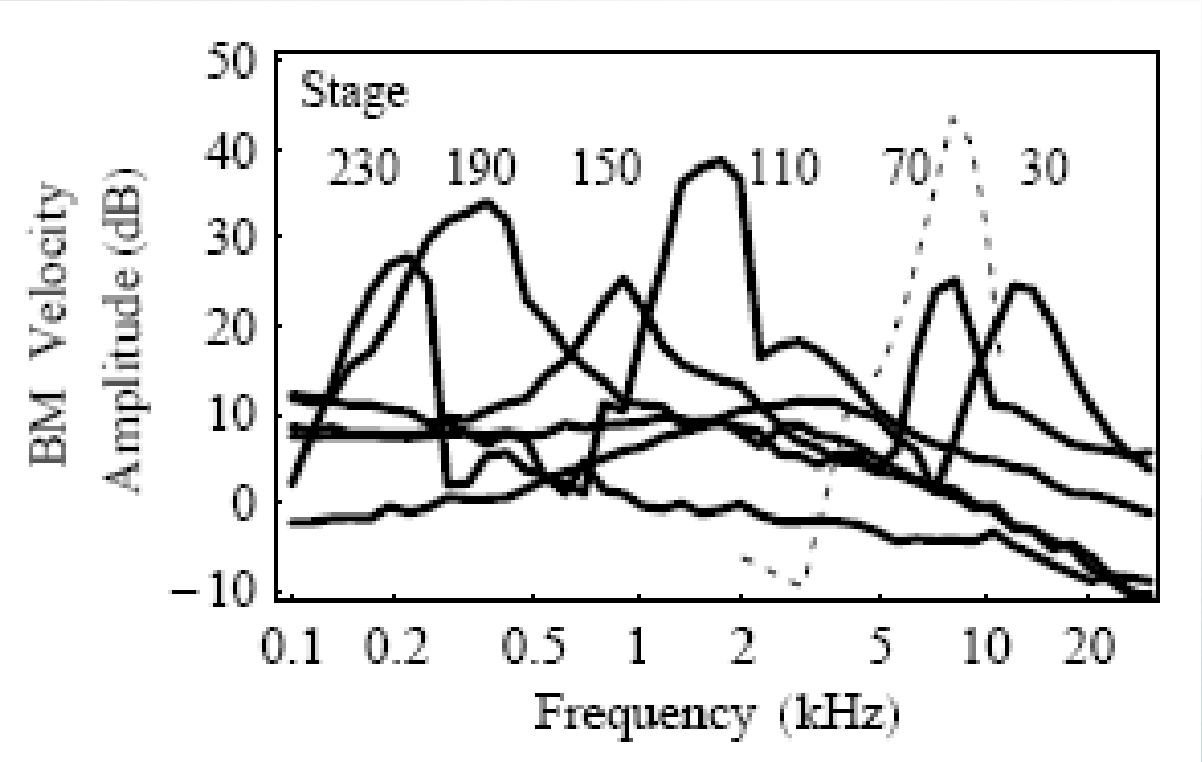


Silicon Cochleae

Shiraishi 2004

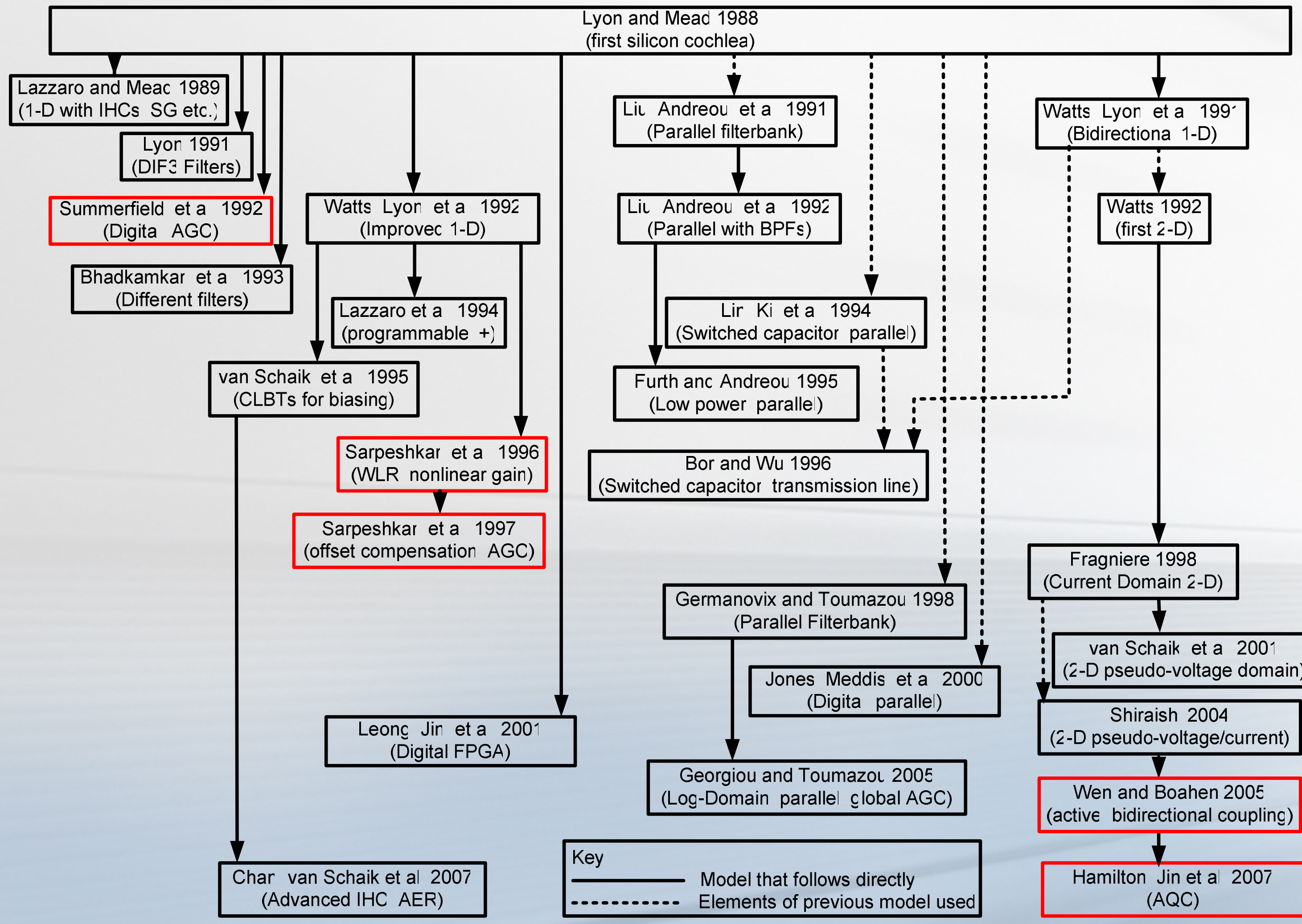


Silicon Cochleae



Wen and Boahen 2005

Silicon Cochleae



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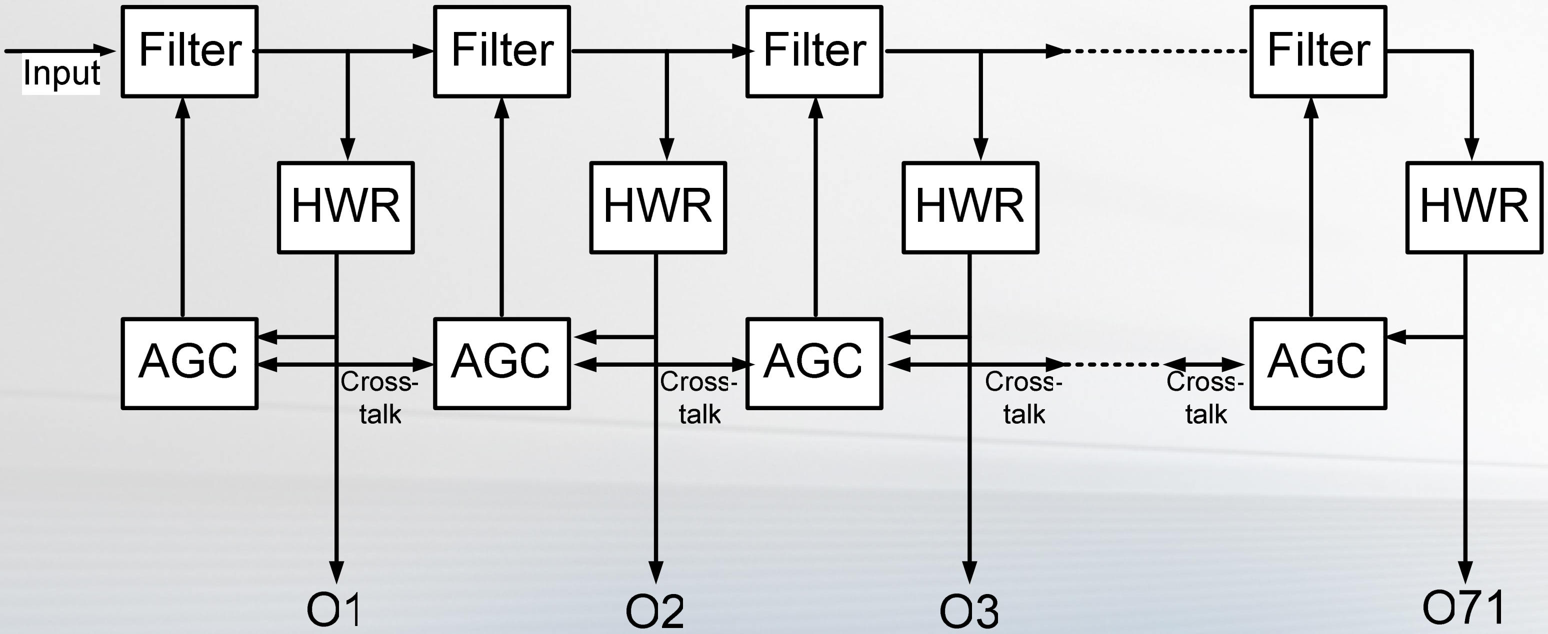
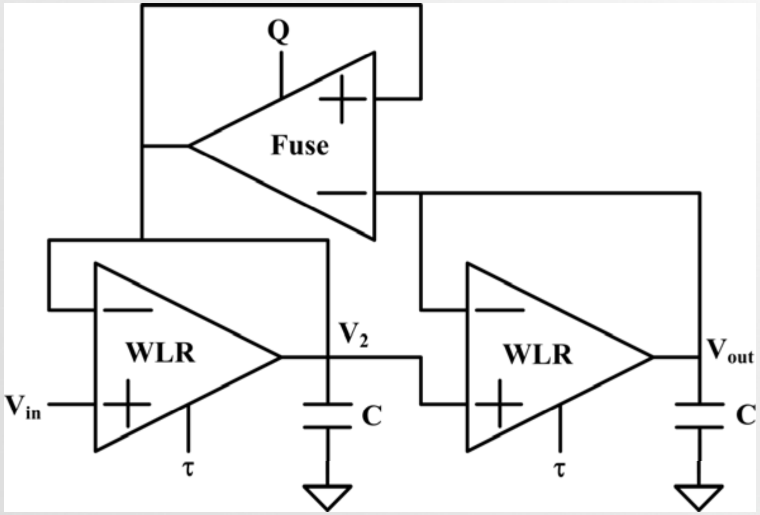
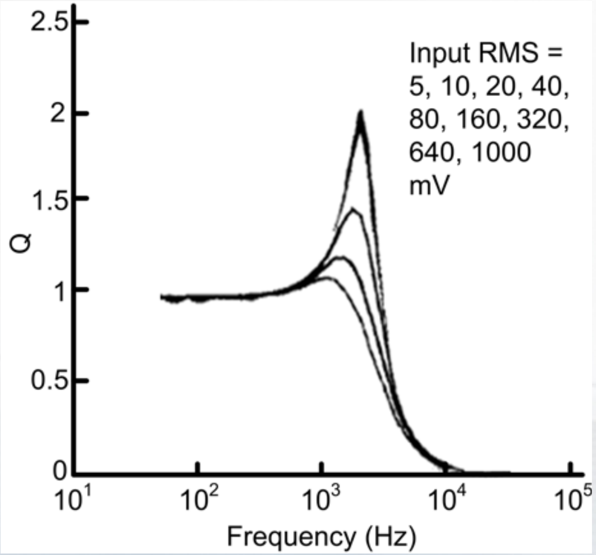
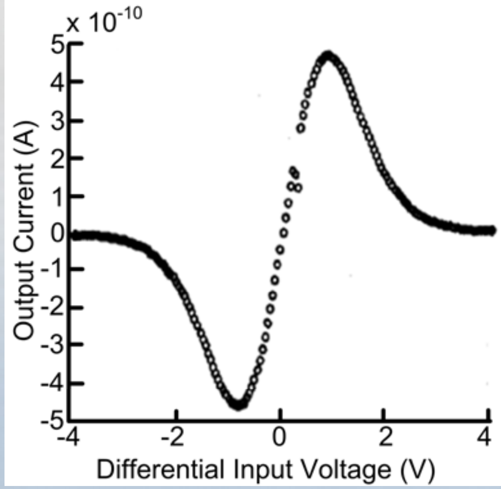


Summerfield and Lyon 1992

Silicon Cochleae

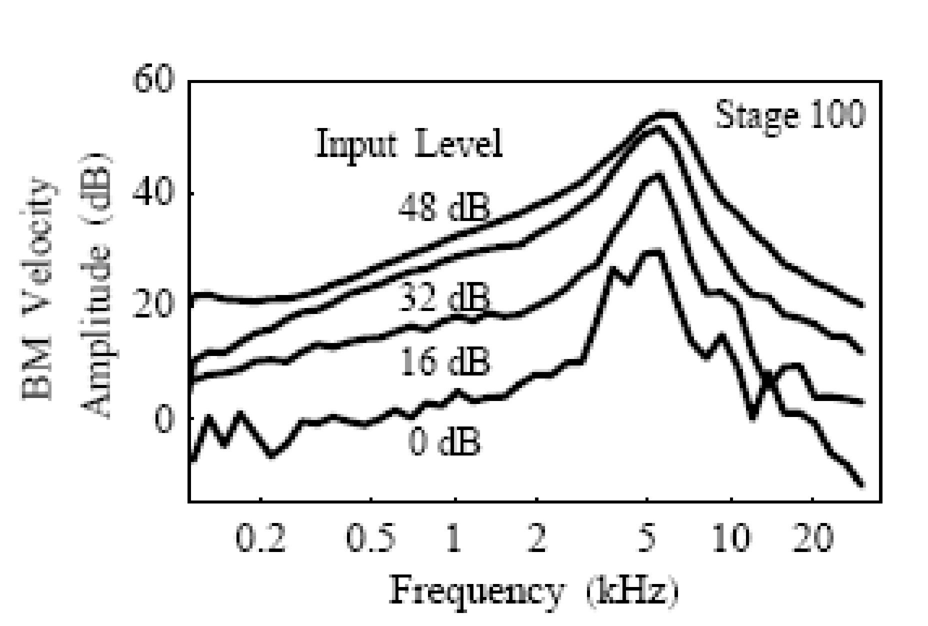






Sarpeshkar, Lyon et al. 1996

Silicon Cochleae



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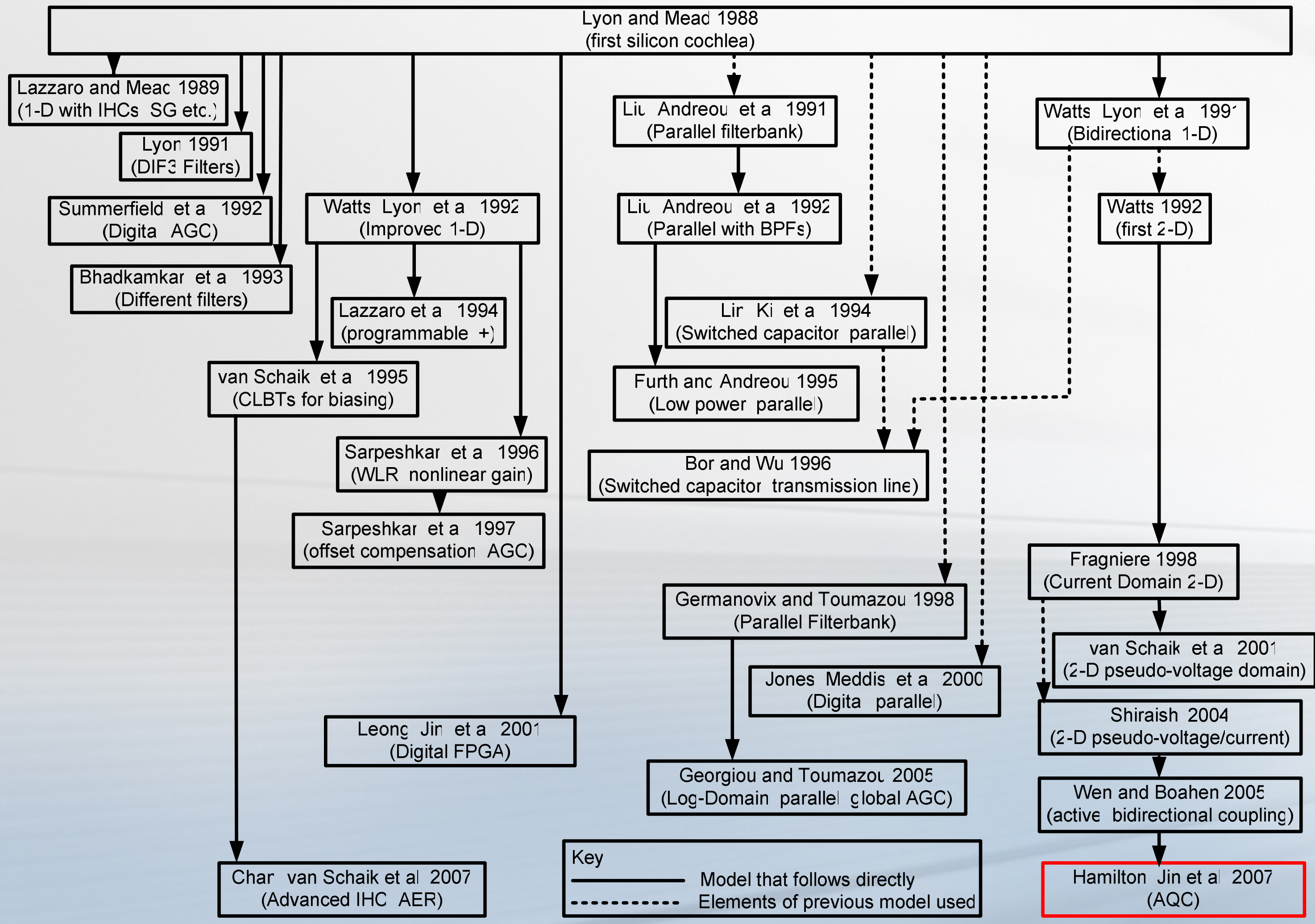
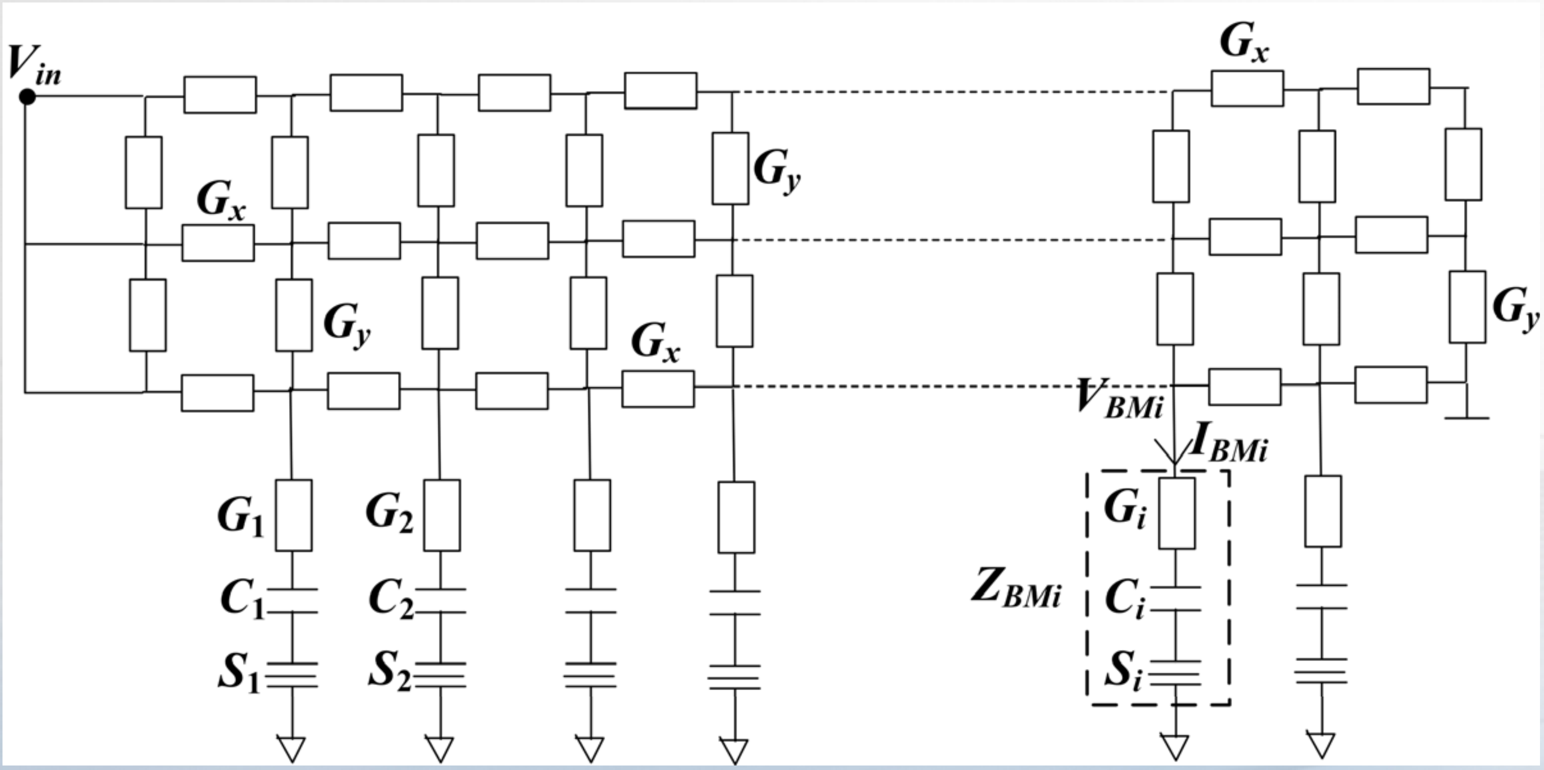


The Passive Model



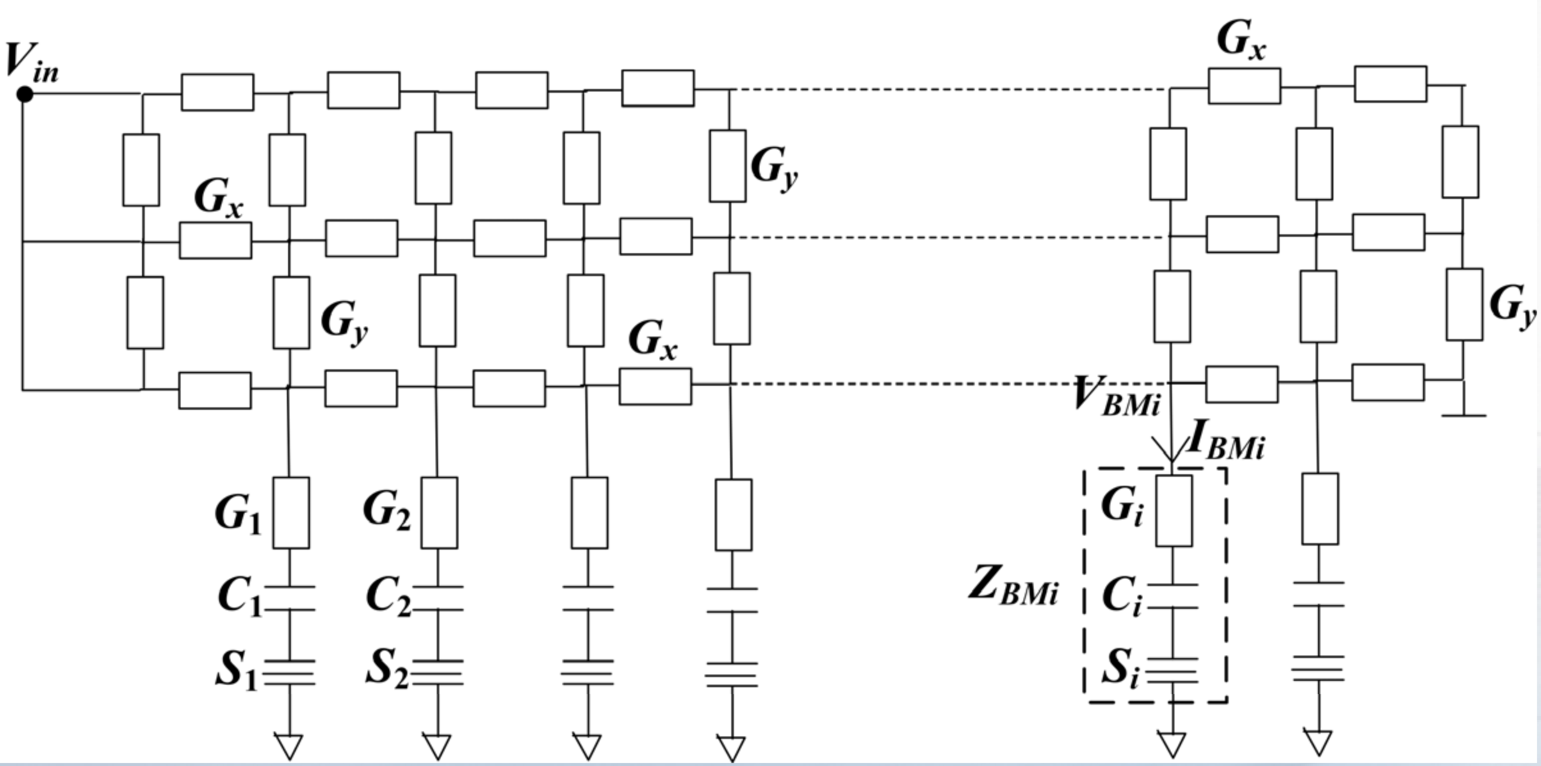
The Passive Model

$$\{p_{SM}(x,0) - p_{ST}(x,0)\}w(x)dx = a_{BM}(x)\left\{m(x)dx + \frac{h(x)}{s}dx + \frac{k(x)}{s^2}dx\right\}$$

$$V_{SM}(x,0) - V_{ST}(x,0) = Z_{BM}(x)J_{BM}(x) = I_{BM}(x)\cdot\left(\frac{1}{G_{BM}(x)} + \frac{1}{sC_{BM}(x)} + \frac{1}{s^2S_{BM}(x)}\right)$$

$$V_{SC} \propto \frac{i_{SC}}{(j\omega)^2} = \frac{-i_{SC}}{\omega^2}$$

The Passive Model

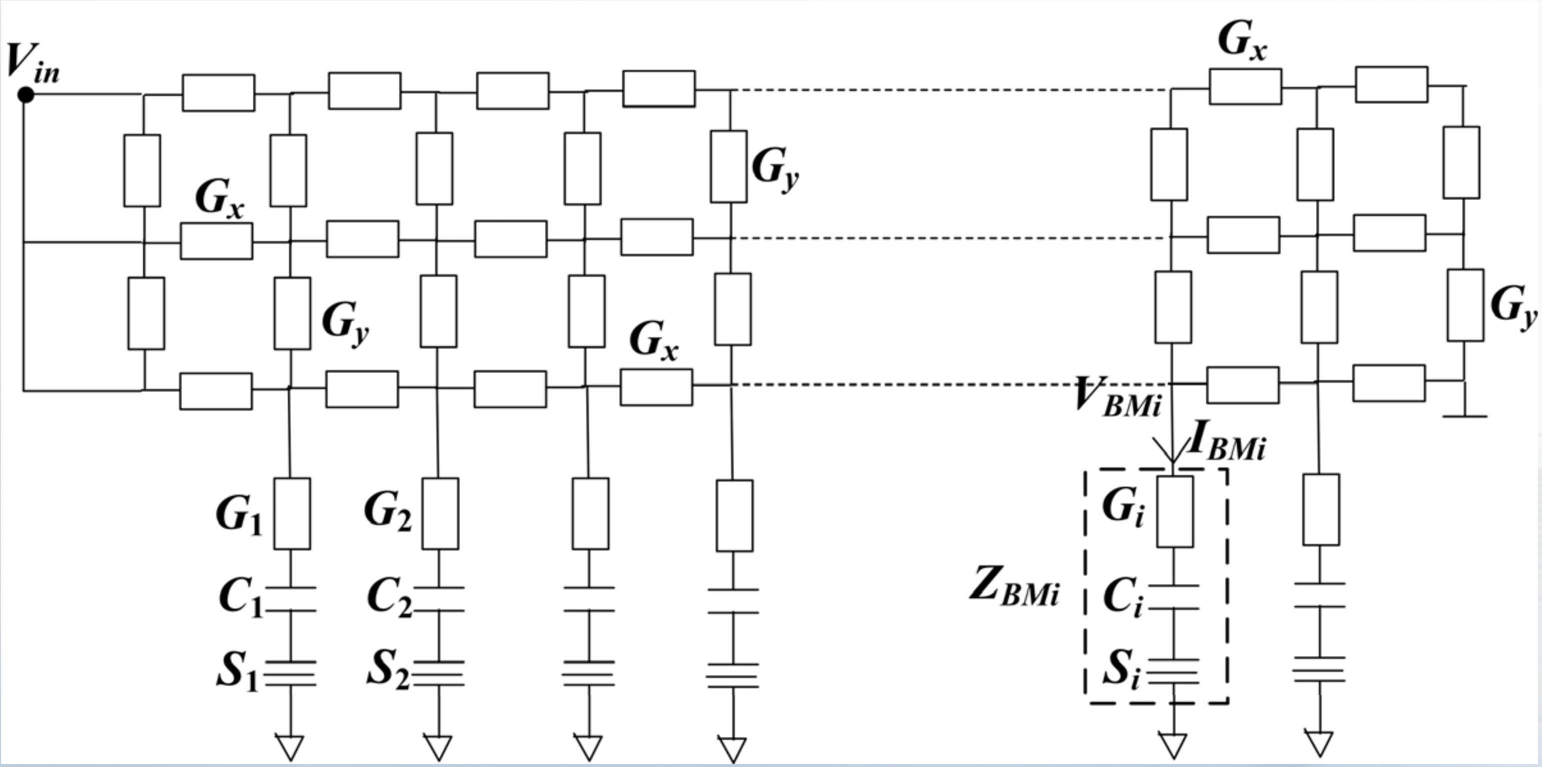


The Passive Model

$$I_{BMi} = \frac{s^2 S_i}{s^2 \frac{S_i}{G_i} + s \frac{S_i}{C_i} + 1} \cdot V_{BMi} = \frac{V_{BMi}}{Z_{BMi}}$$

$$\frac{I_{BMi}}{s} = \frac{s S_i}{s^2 \frac{S_i}{G_i} + s \frac{S_i}{C_i} + 1} \cdot V_{BMi}$$

The Passive Model



The Active Model

Capacitance, effective viscosity and quality factor are equivalent

$$\frac{I_{BMi}}{s} = \frac{sS_i}{s^2 \frac{S_i}{G_i} + s \frac{S_i}{C_i} + 1} \cdot V_{BMi} \qquad T(s) = \frac{Out(s)}{In(s)} = \frac{s\tau}{s^2 \tau^2 + s \frac{\tau}{Q} + 1}$$

$$Q \propto C_i \propto \frac{1}{h}$$

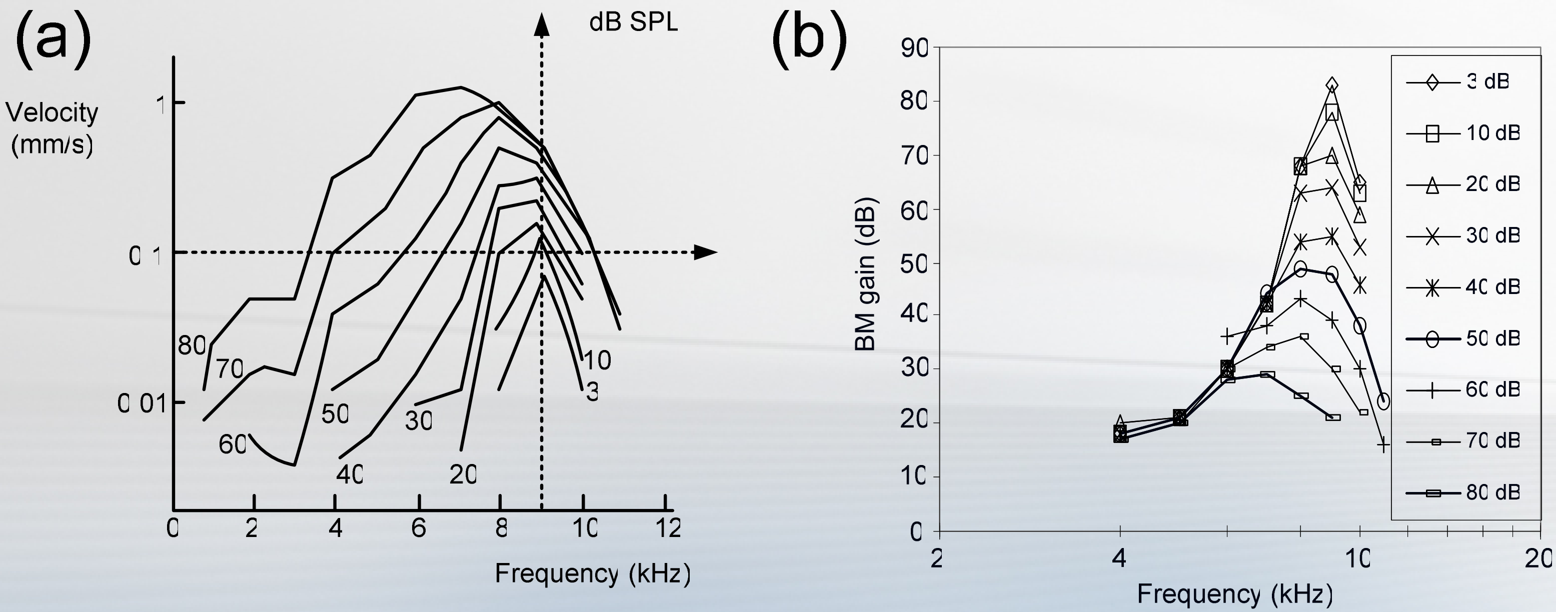
The Passive Model

$$\{p_{SM}(x,0) - p_{ST}(x,0)\}w(x)dx = a_{BM}(x)\left\{m(x)dx + \frac{h(x)}{s}dx + \frac{k(x)}{s^2}dx\right\}$$

$$V_{SM}(x,0) - V_{ST}(x,0) = Z_{BM}(x)J_{BM}(x) = I_{BM}(x)\cdot\left(\frac{1}{G_{BM}(x)} + \frac{1}{sC_{BM}(x)} + \frac{1}{s^2 S_{BM}(x)}\right)$$

$$V_{SC} \propto \frac{i_{SC}}{(j\omega)^2} = \frac{-i_{SC}}{\omega^2}$$

Hopf Bifurcation Hypothesis

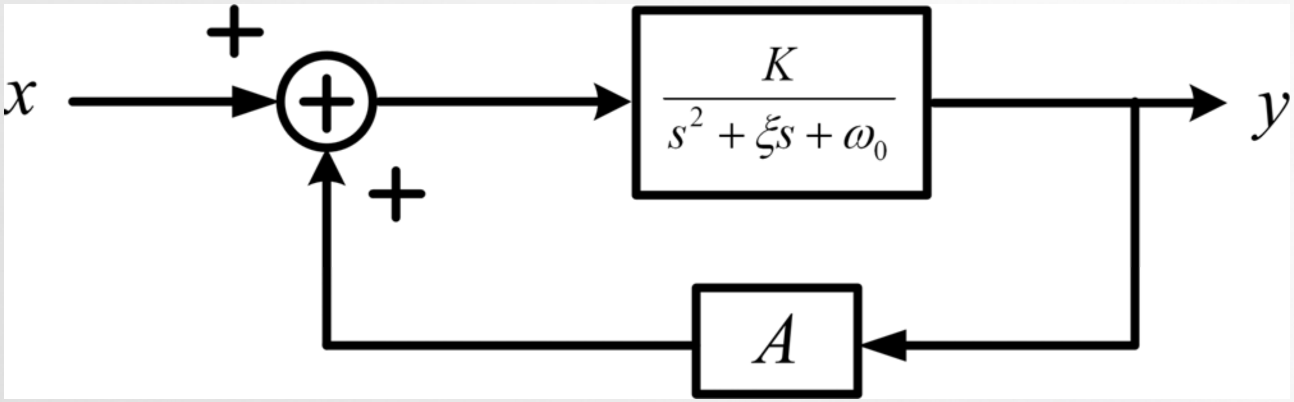


Hopf Bifurcation and Parametric Amplification

μ	**Region of Operation**
> 0	Unstable, limit cycle
= 0	Critical point, bifurcation
< 0	Sub-critical, stable equilibrium

$$\dot{y} = (\mu + j\omega_0)y - y^3 + x$$

Hopf Bifurcation and Parametric Amplification



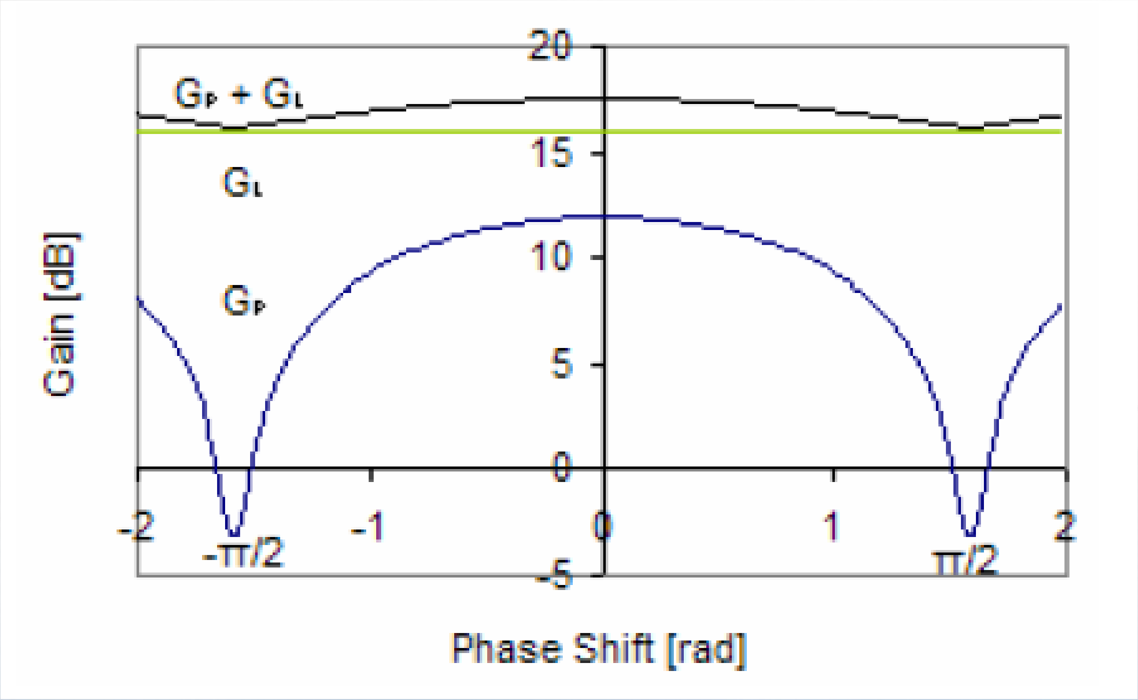
$$M\frac{d^2y}{dt^2}+\xi\frac{dy}{dt}+(k-g\mu)y+gy|y|^2-x=0$$

$$A=g\left(\mu-|y|^2\right)$$

Tapson, Hamilton et al. 2008

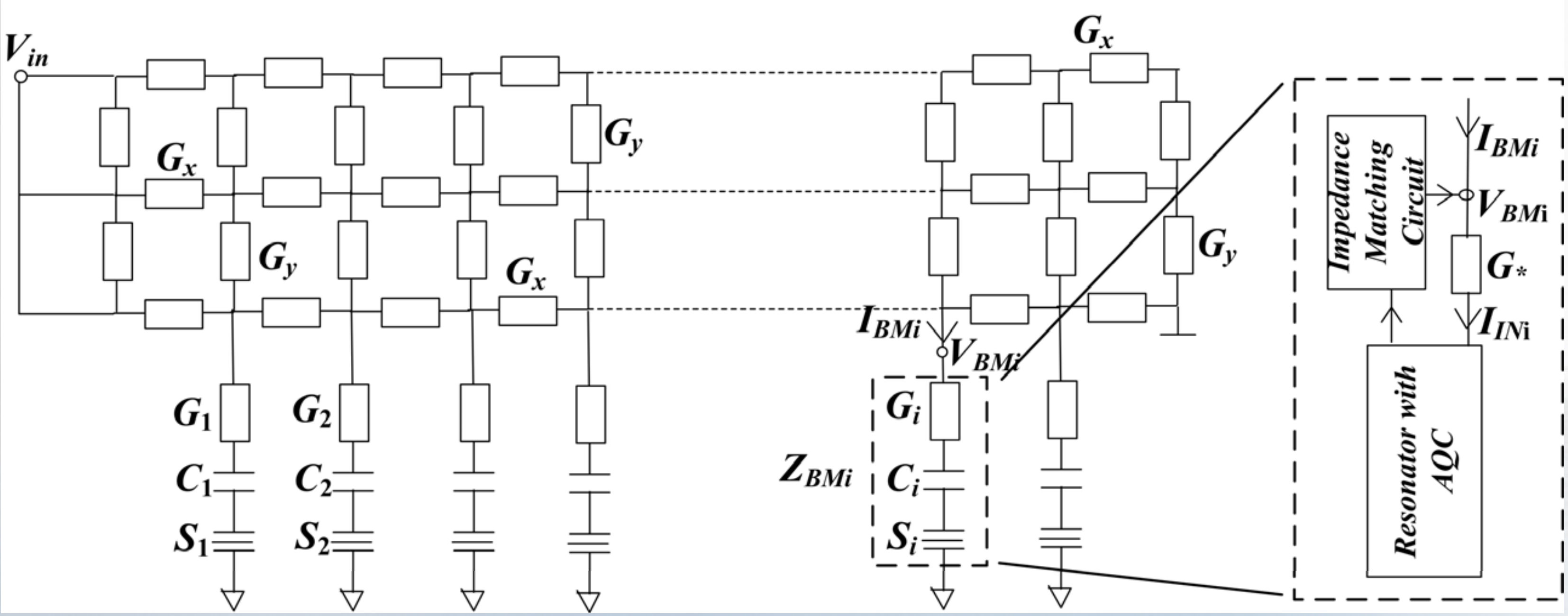
Hopf Bifurcation and Parametric Amplification

$$\left|Y\,\sin\omega t\right|^2 = Y^2\sin^2\omega t = \frac{1}{2}Y^2\left(1+\cos 2\omega t\right)$$

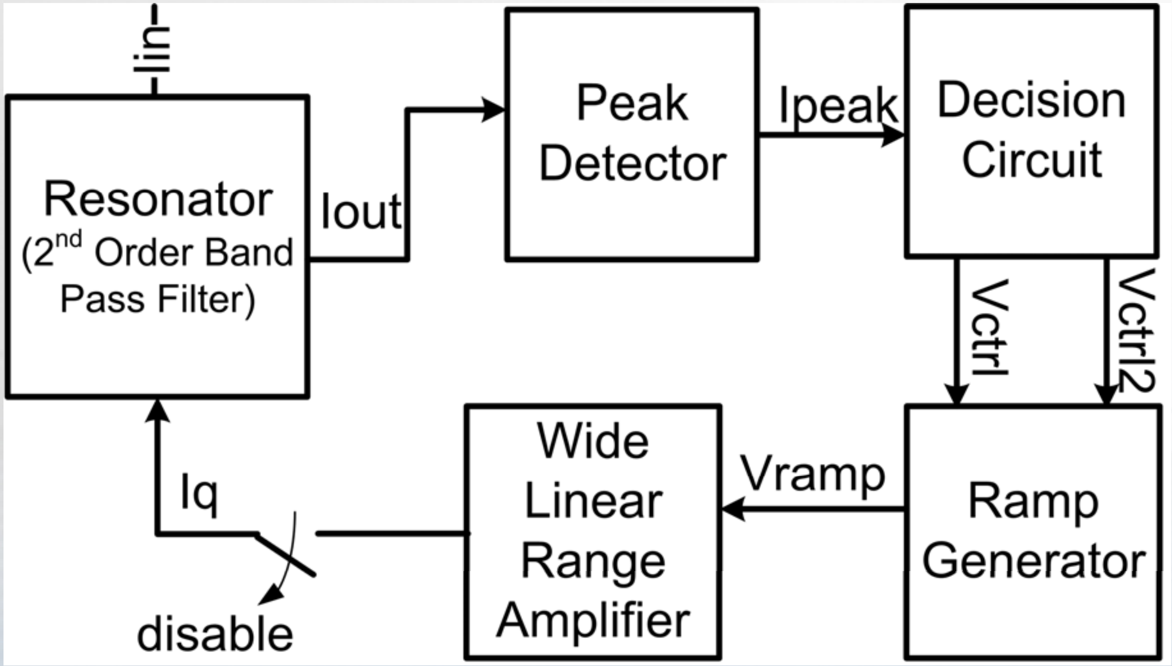


Here: Hopf ≡ Parametric Amplification

The Active Model



Physical Implementation



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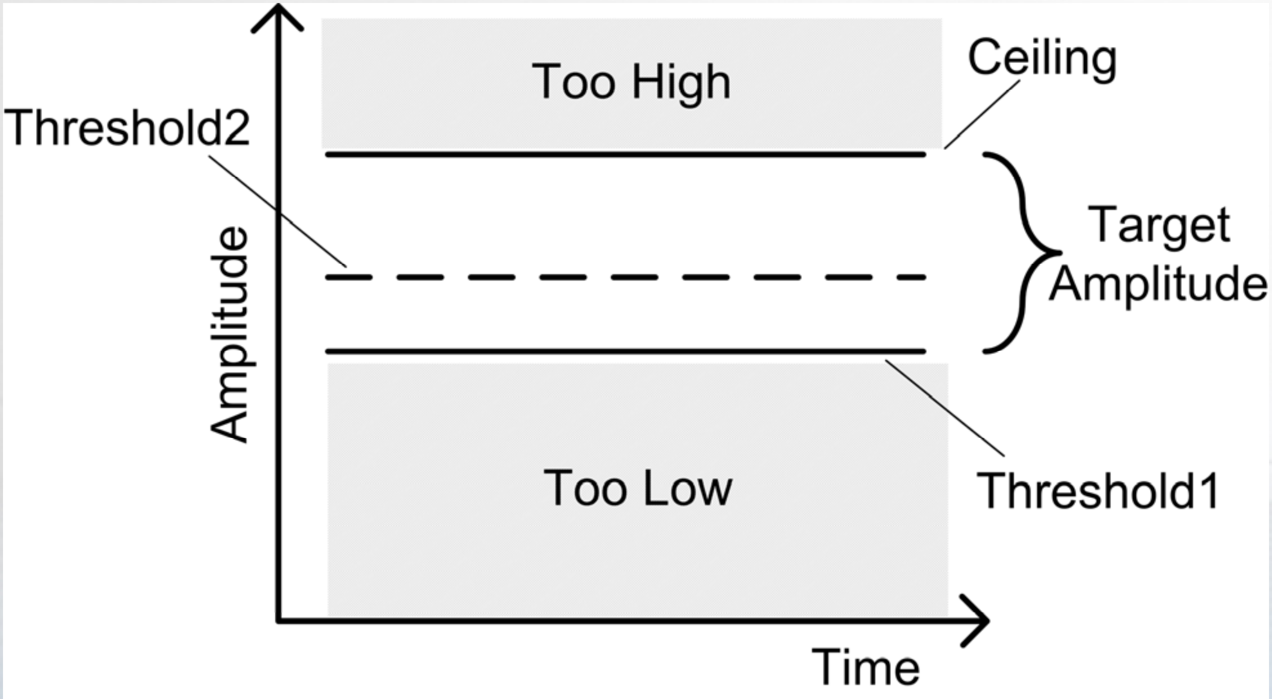

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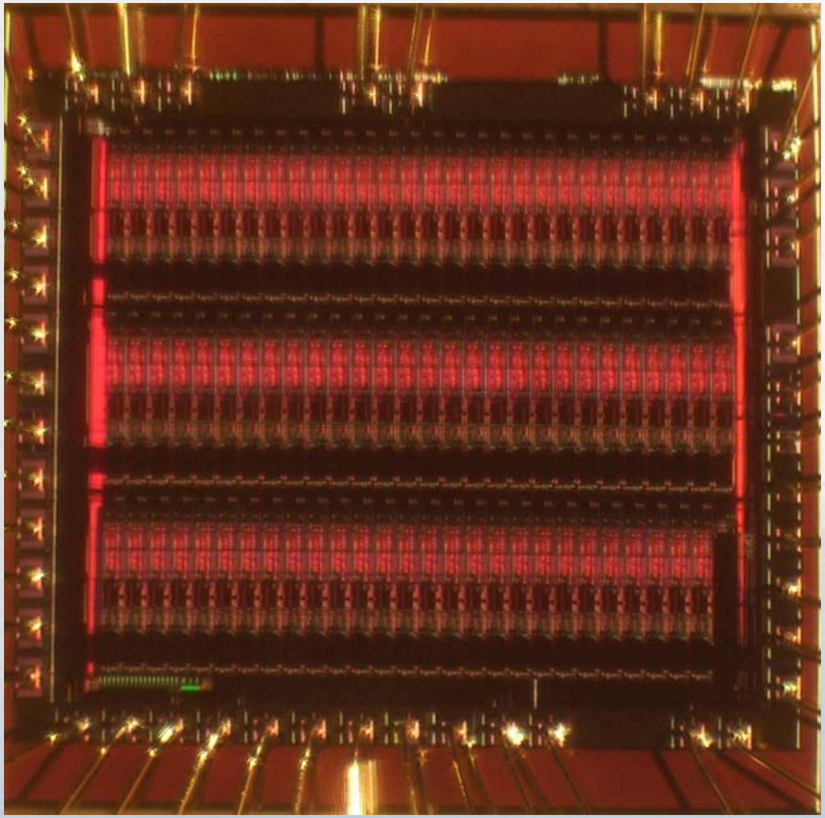

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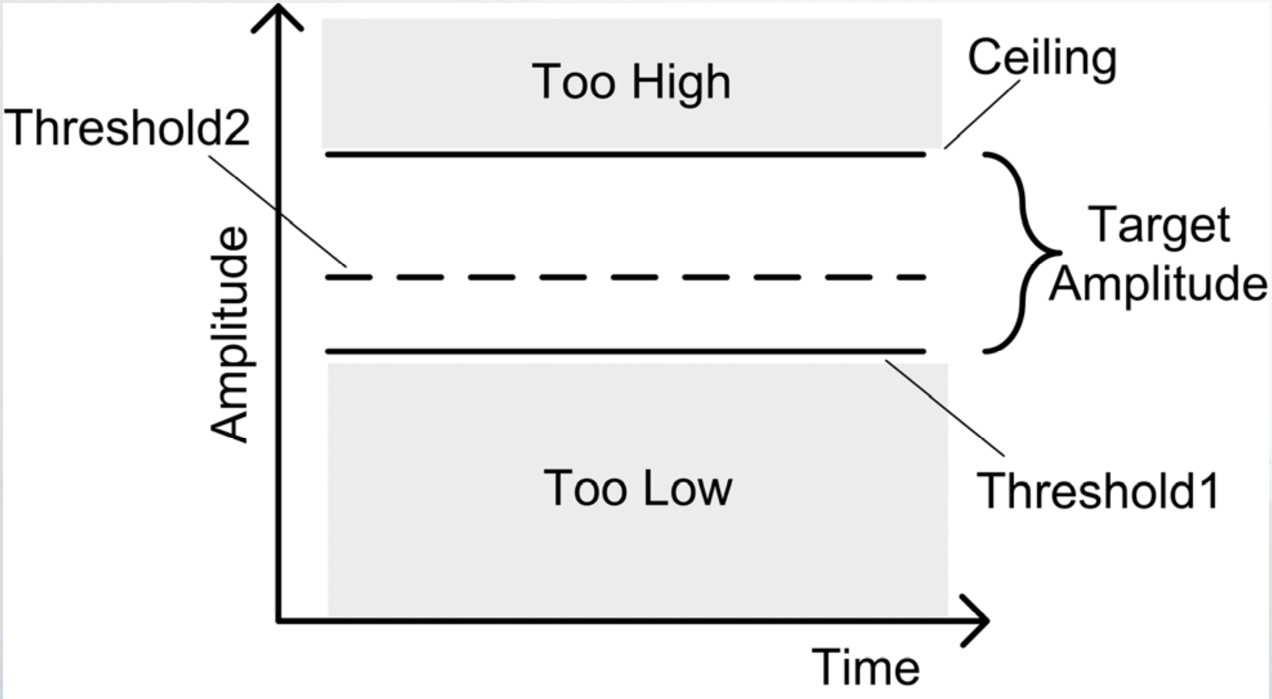

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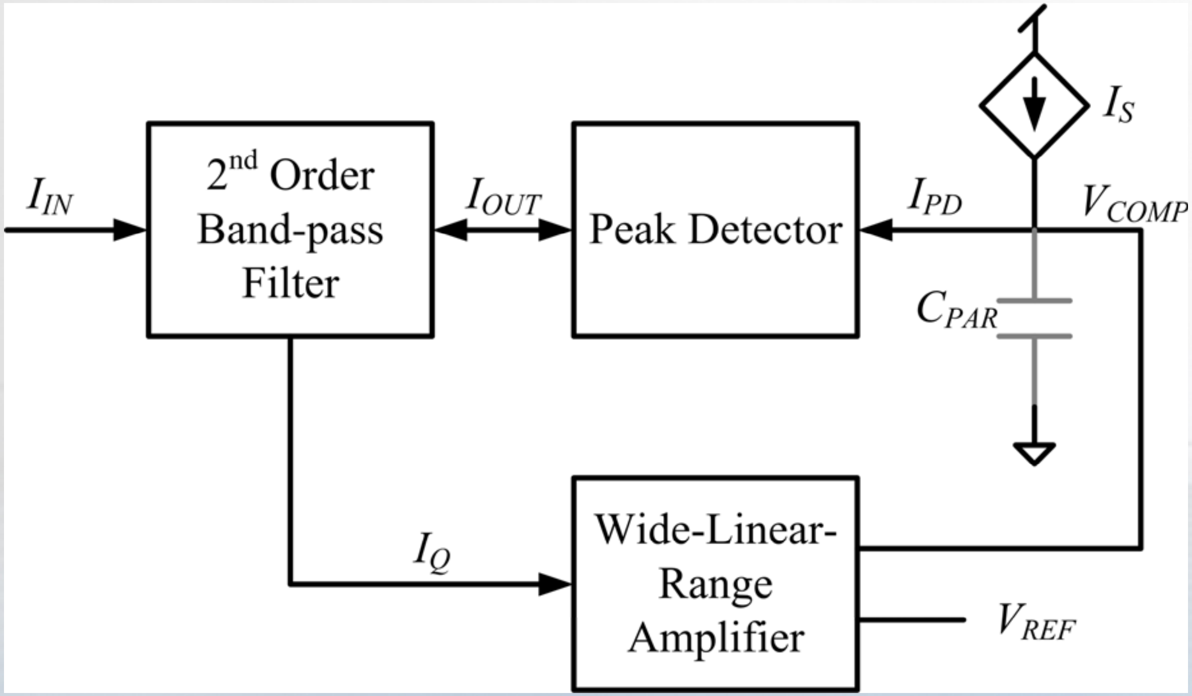

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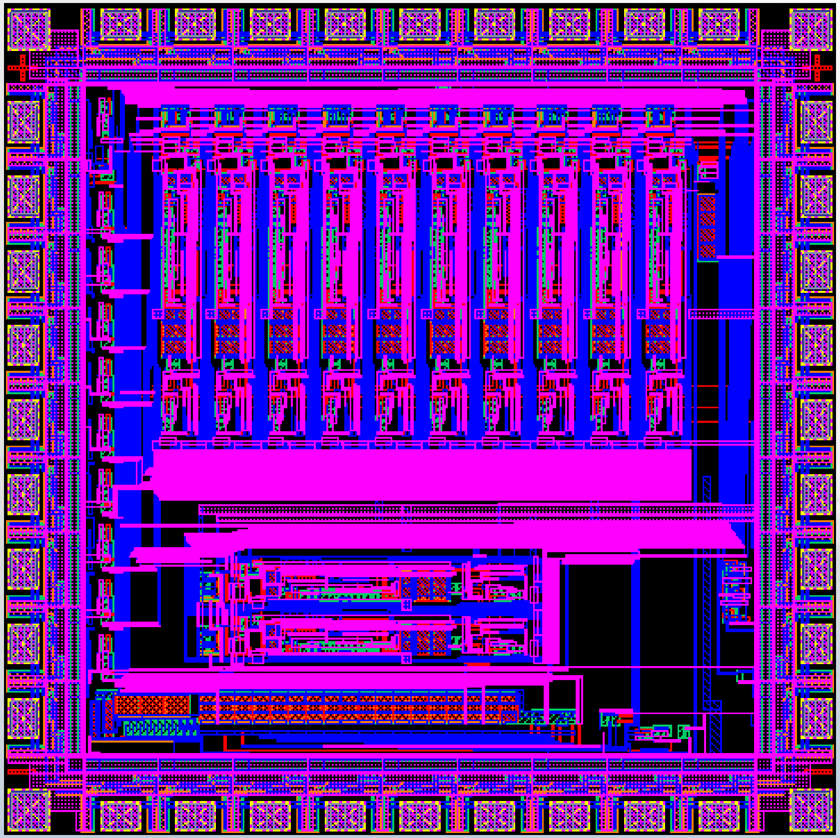

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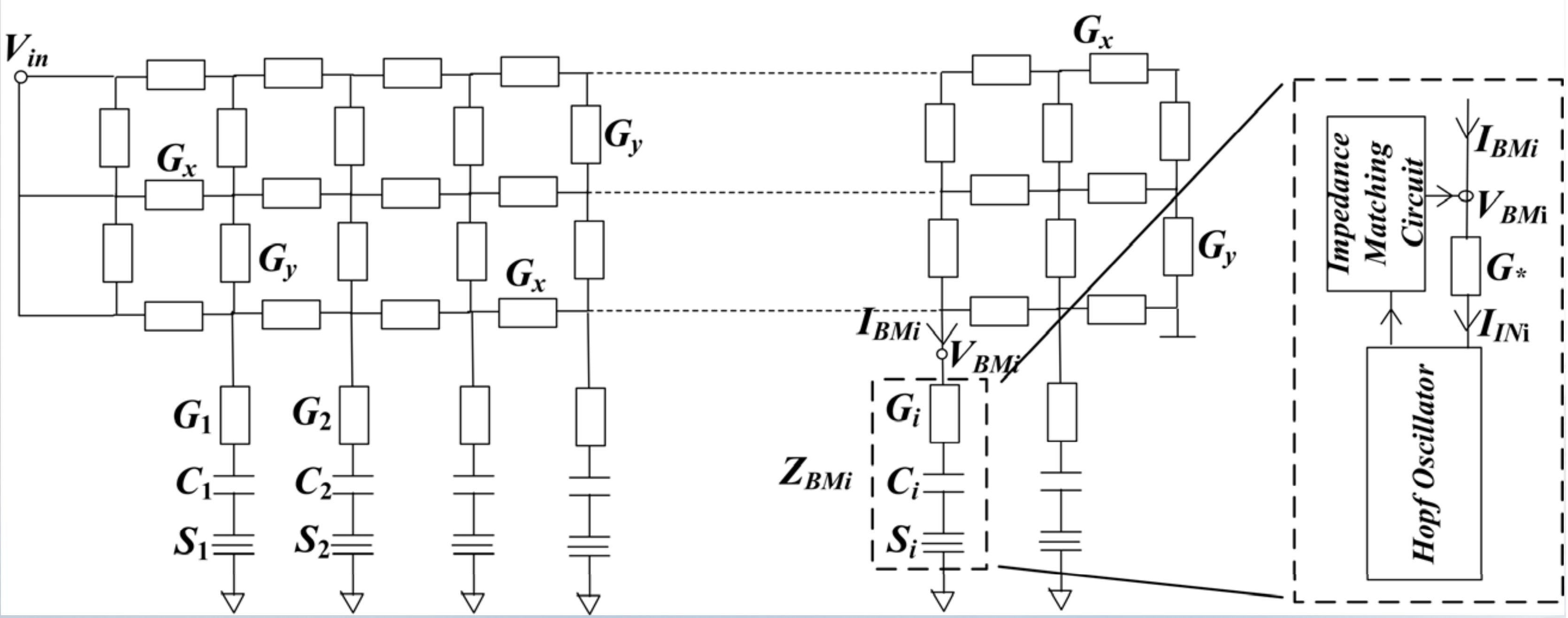

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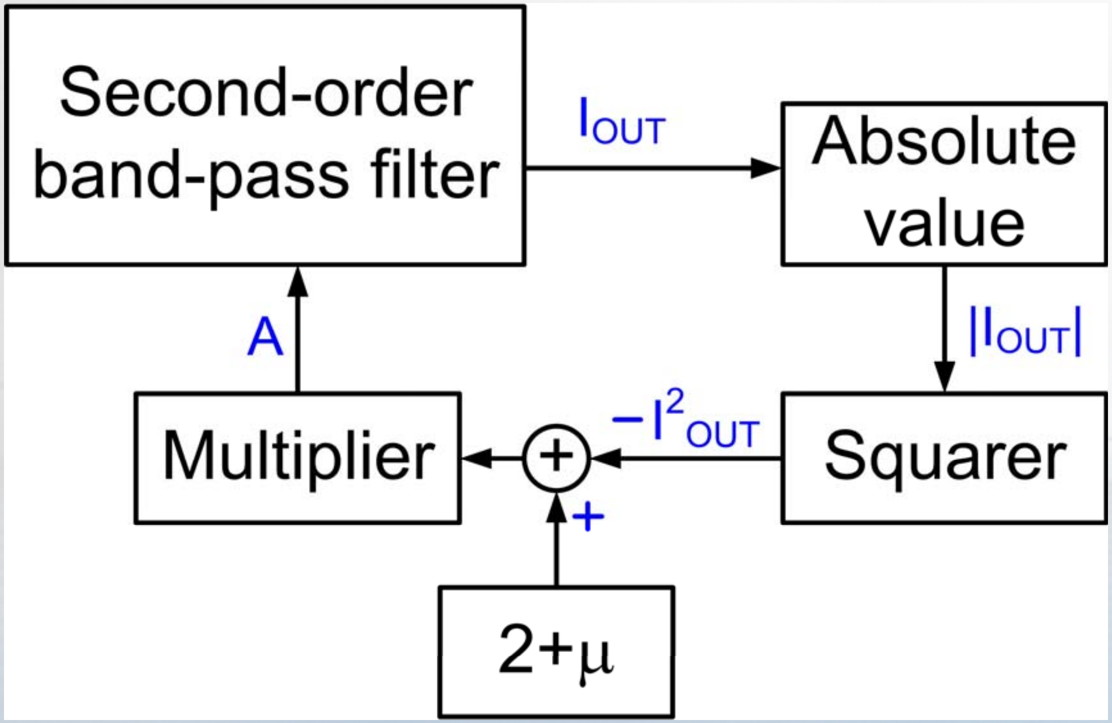

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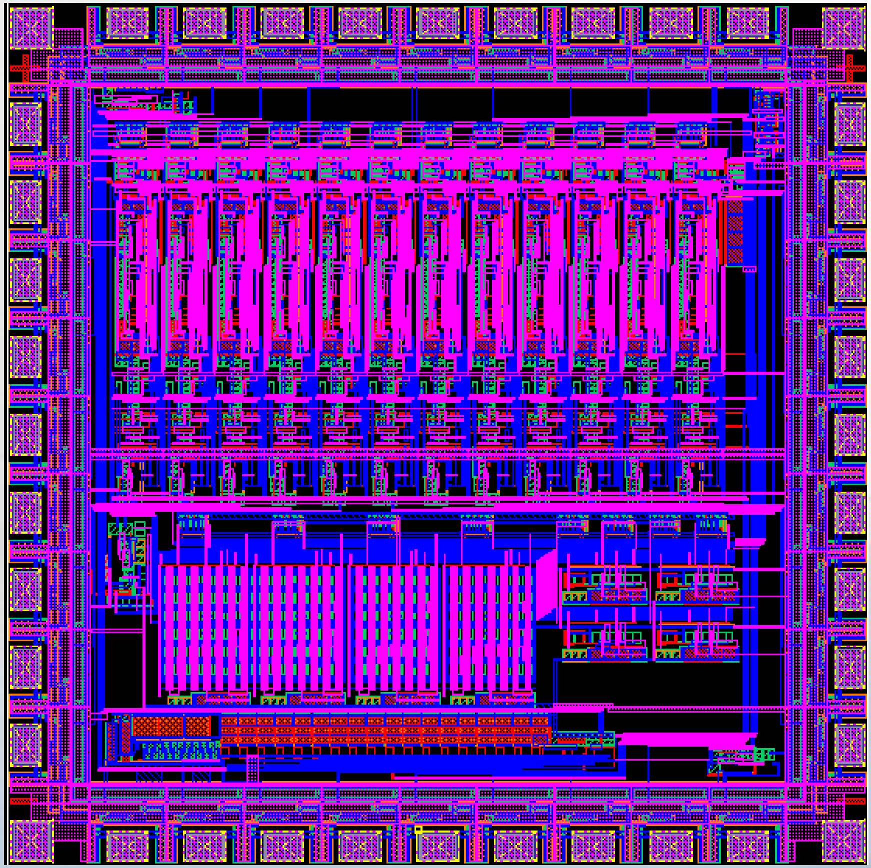
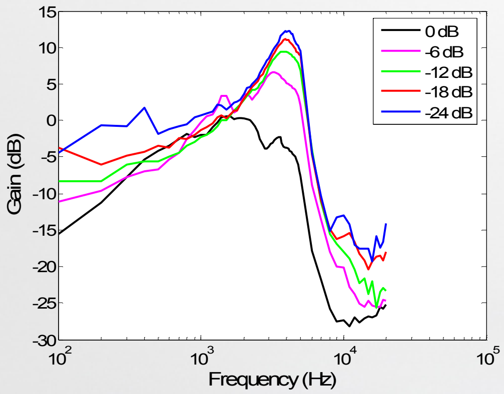
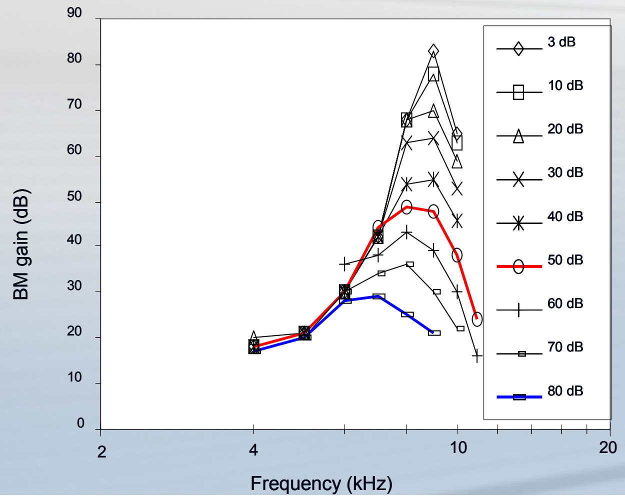
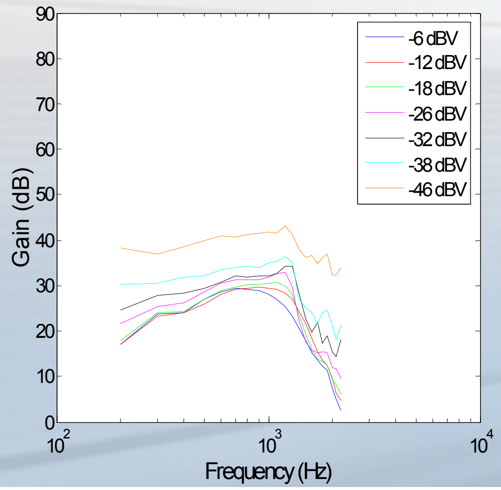


Results

Large-Signal Compression







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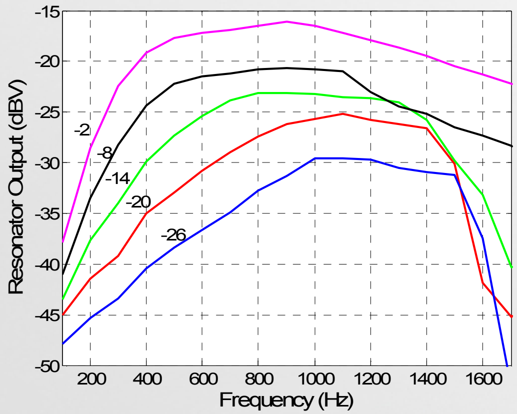

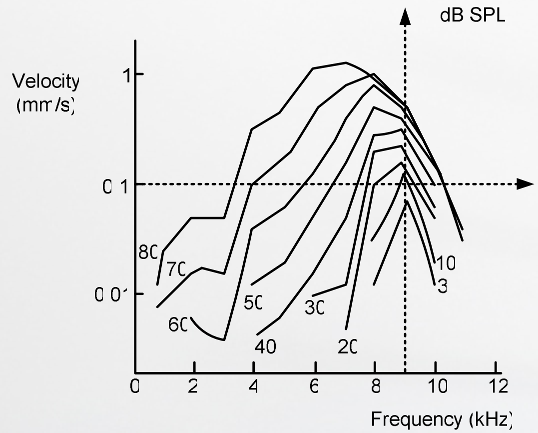

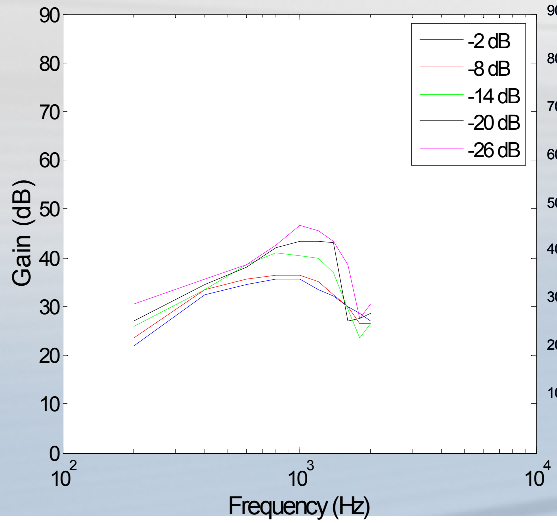

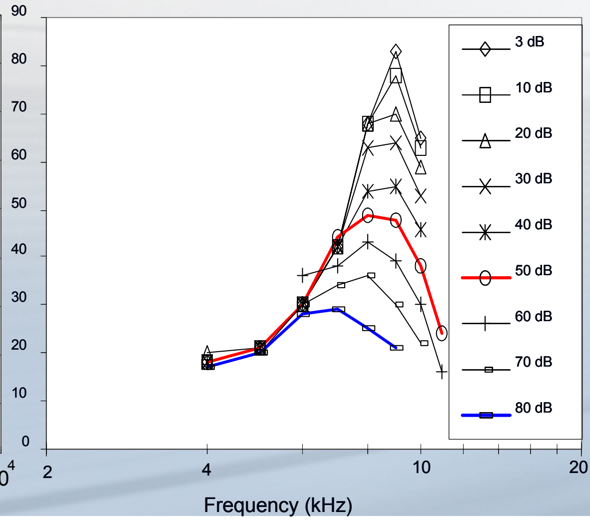

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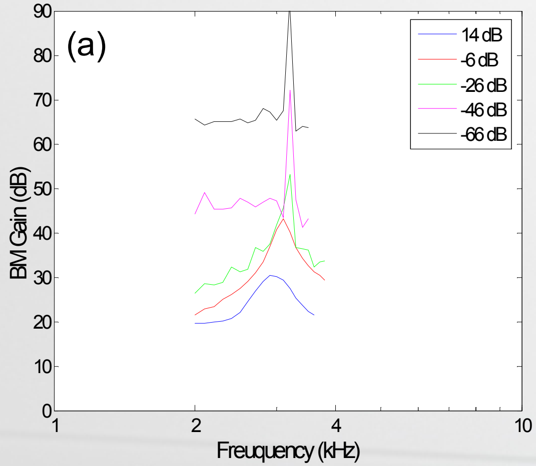
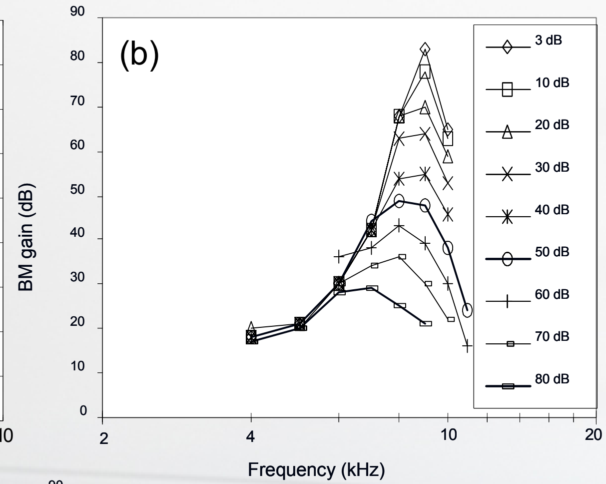
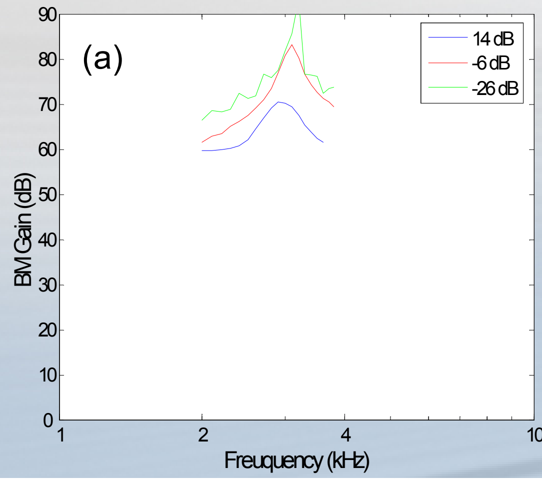
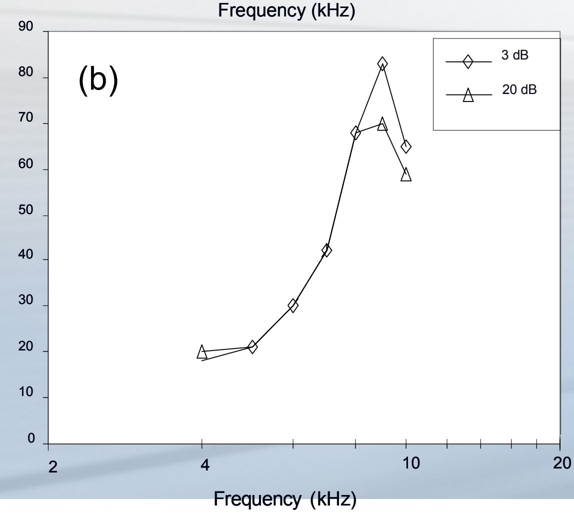


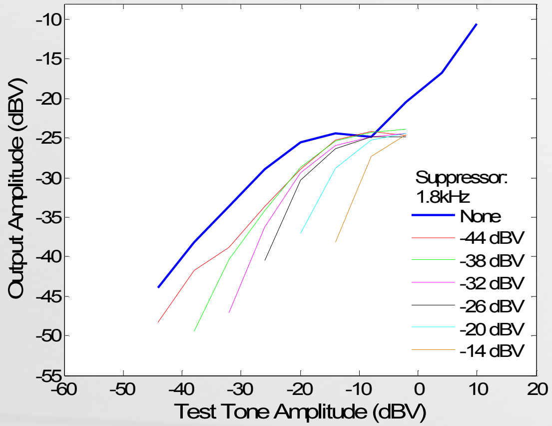


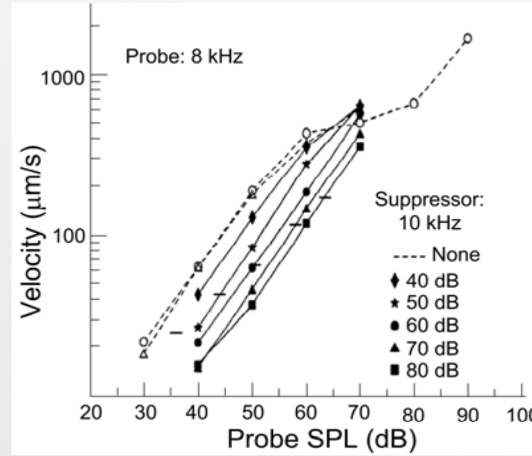


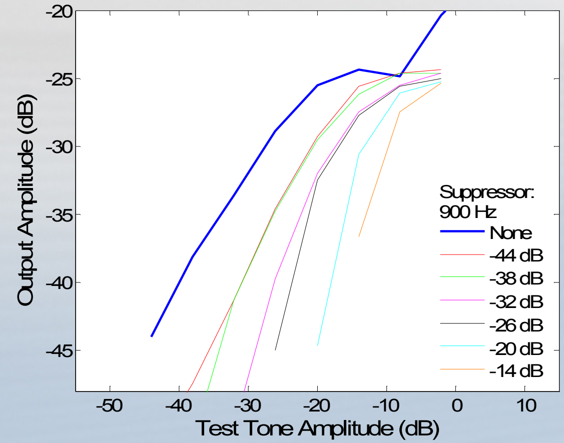


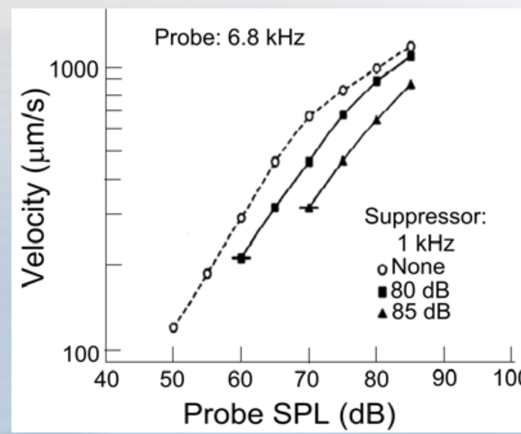
Results

Two-tone suppression



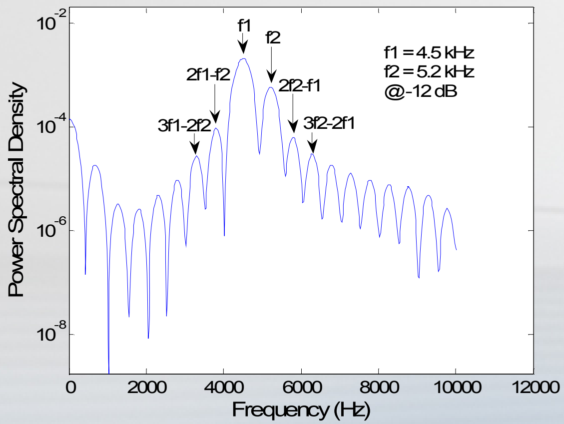


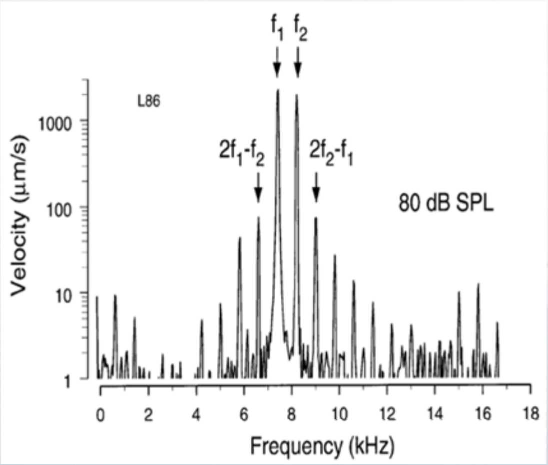




Results

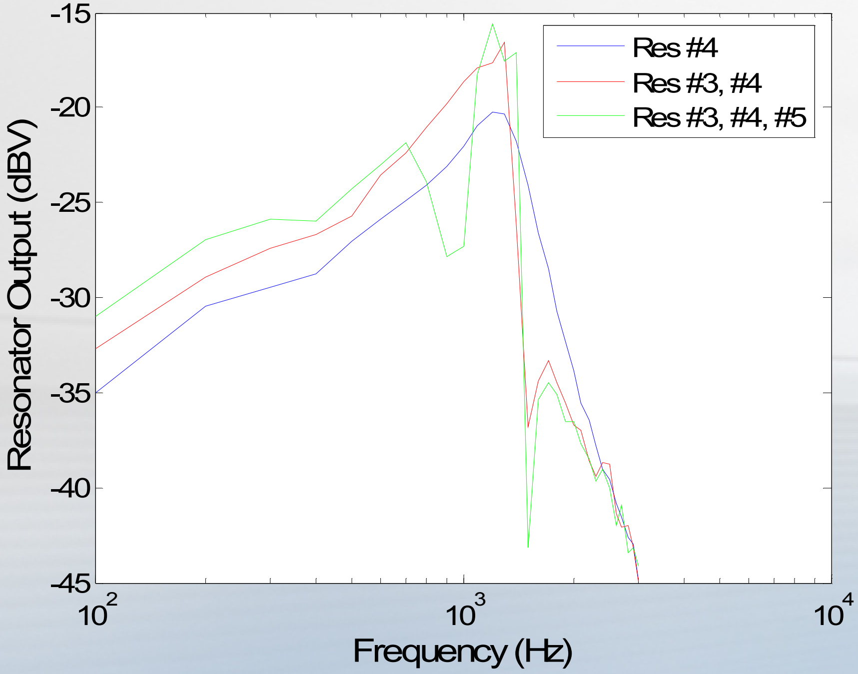
Combinational Tones





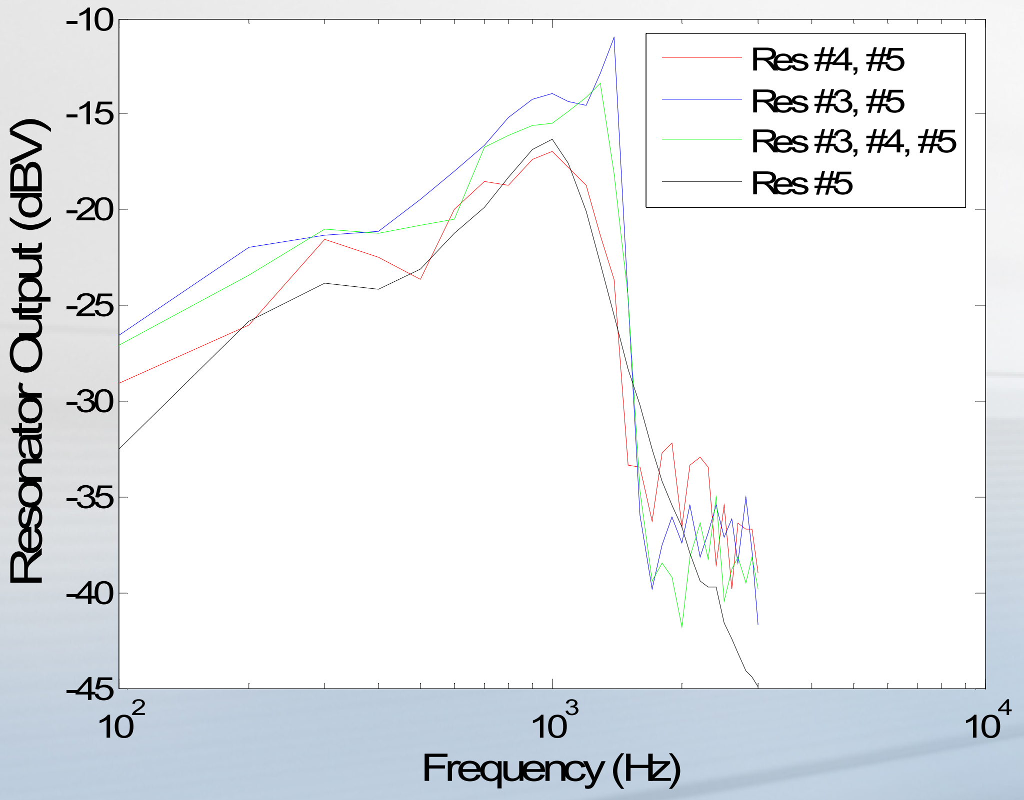
Results

Coupling between resonator sections



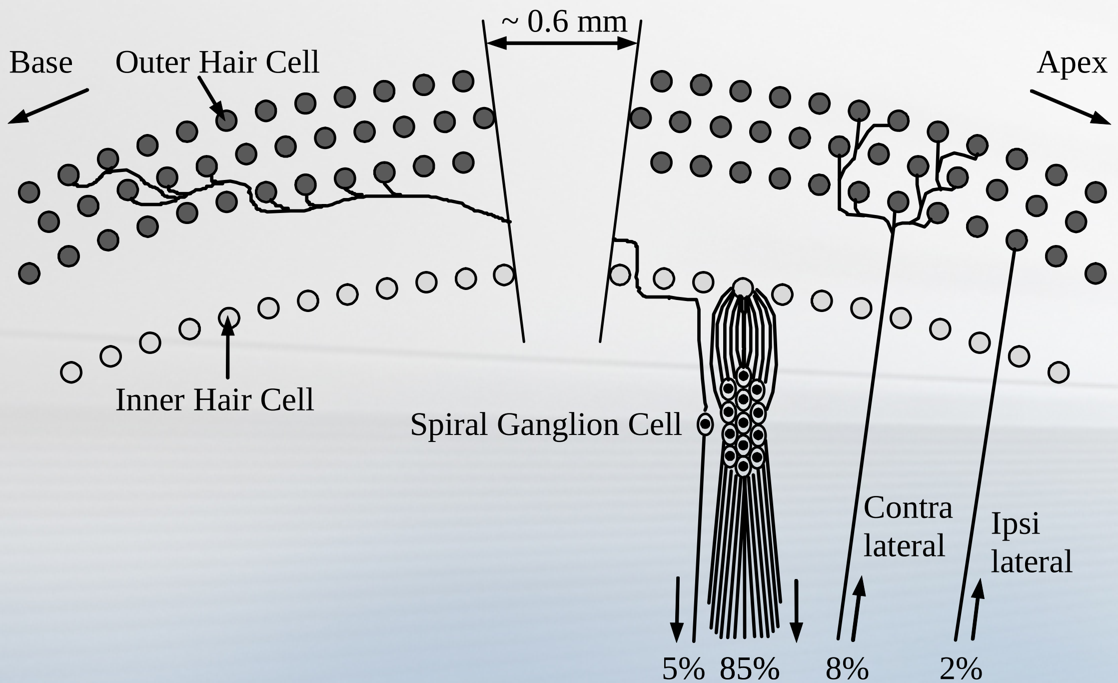
Results

Coupling between resonator sections



Results

Innervation of Hair Cells



The "To Do" List

- Bigger silicon cochlea implementing Hopf/parametric resonators
- Attach neurons to output
- Explore coupling, masking, suppression, binaural hearing, the "Cocktail Party" problem etc. in even greater detail

Conclusions

- Silicon Cochleae are useful!
- We’ve built 3 silicon cochleae that exhibit many of the nonlinear and active properties of the mammalian cochlea
- We’ve shown that we can use these cochleae to understand biology a little better

The End

<u>Easy</u> Questions????