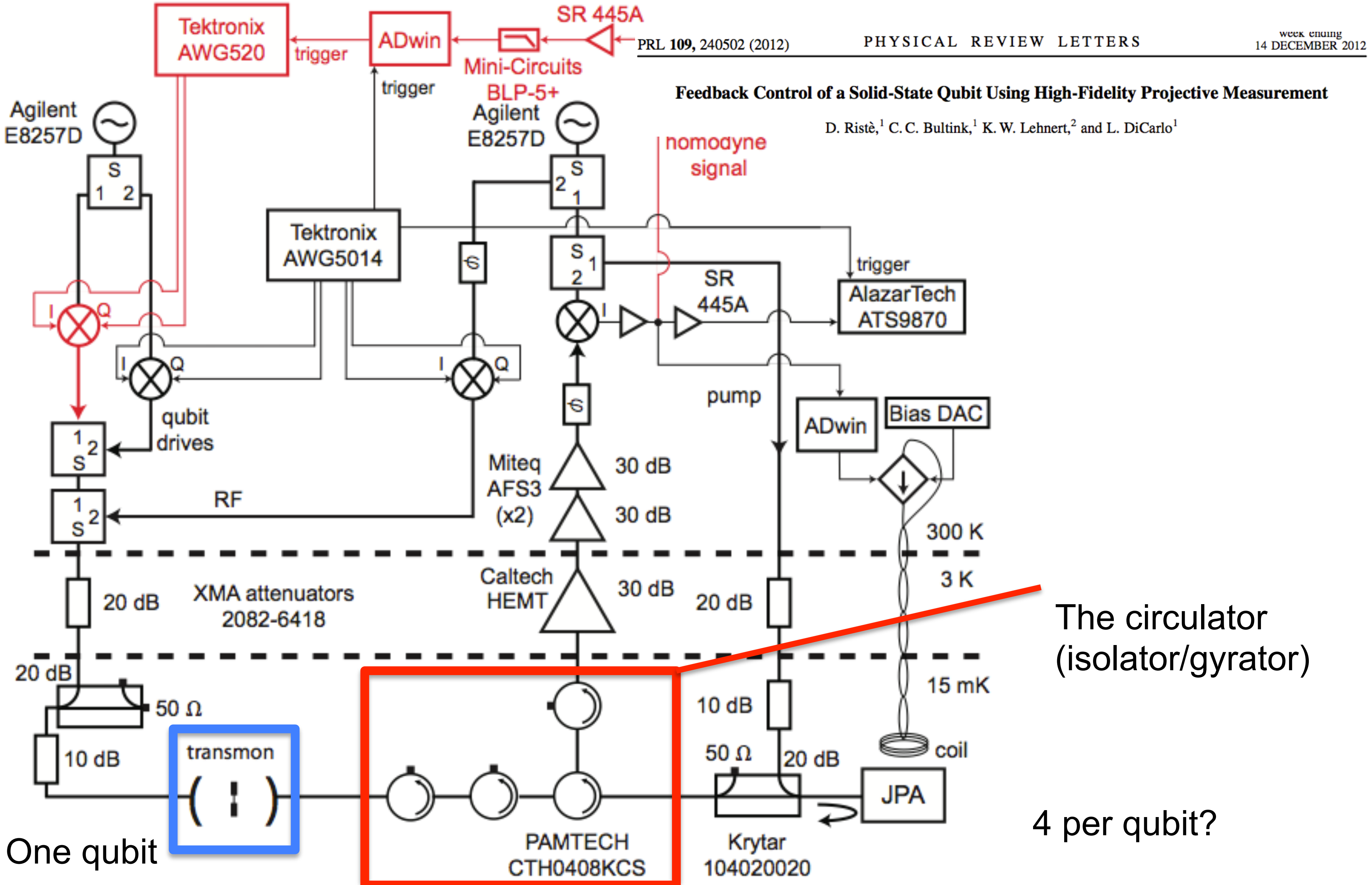
Semiconductor Hall Effect Gyrators and Circulators

Outline

- Role of circulators in qubit experiments
- What is a circulator, and what is a gyrator?
- Faraday effect (bulky) vs. Hall effect – some history
- Our work – capacitive vs. ohmic/galvanic contact
- Dynamics of chiral edge magnetoplasmons
- Experimental situation: new ideas for impedance matching
- New: connection with microscopic theory

G. Viola and D. P. DiVincenzo, *Hall Effect Gyrators and Circulators,* Phys. Rev. X **4**, 021019 (2014).
S. Bosco, F. Haupt, and D. P. DiVincenzo, *Self impedance matched Hall-effect gyrators and circulators,* arXiv:1609.06543, Phys Rev Applied **7**, 024030 (2017).
Bosco & DiVincenzo, *Non-reciprocal quantum Hall devices with driven edge magnetoplasmons in two-dimensional conductors,* Phys. Rev. B, accepted.

A challenge of scaling up quantum computing: classical instrumentation is very complex!



The circulator (isolator/gyrator)

4 per qubit?

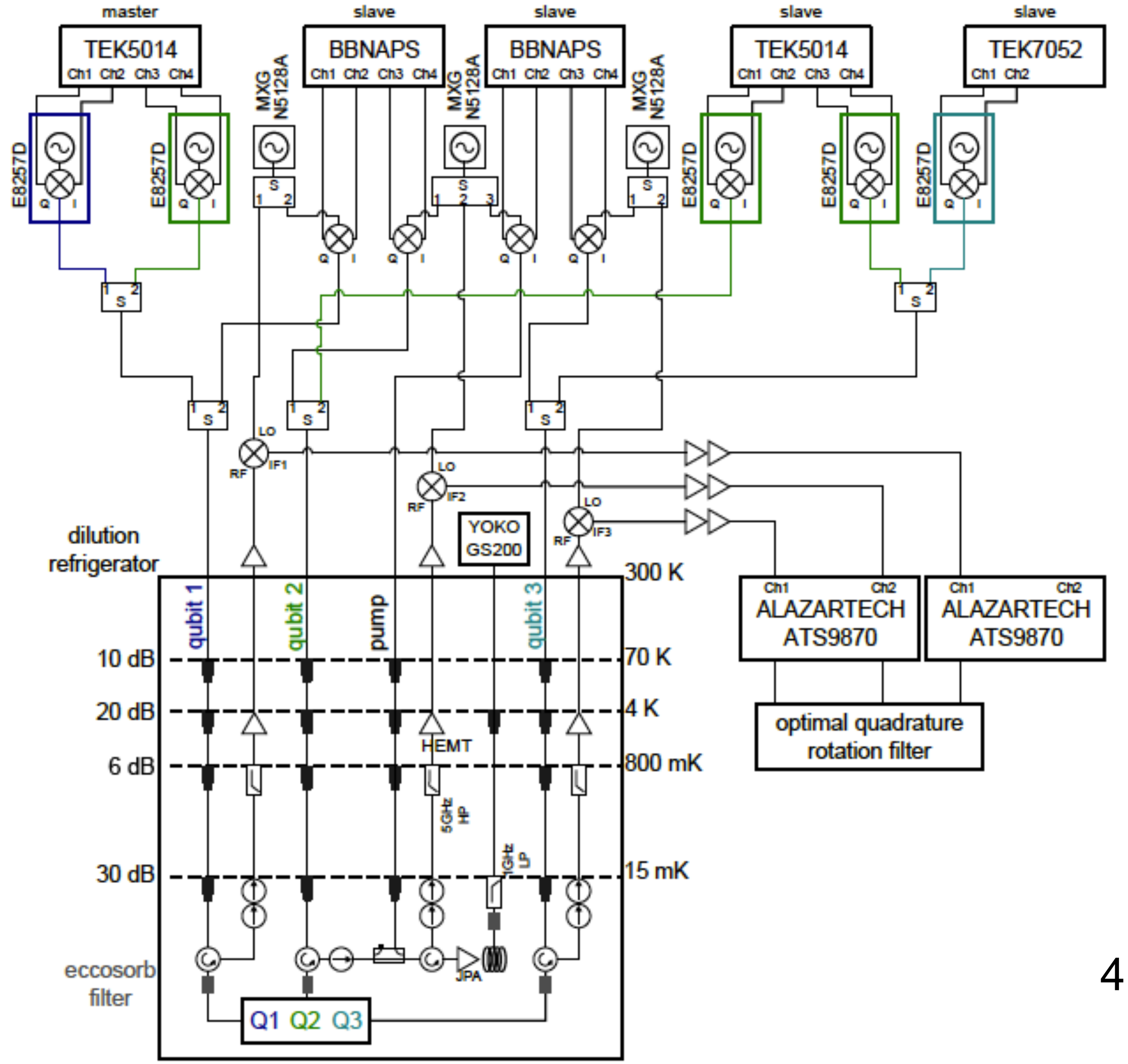
One qubit

IBM:
11 circulators!

Implementing a strand of a scalable fault-tolerant quantum computing fabric

Jerry M. Chow,[1] Jay M. Gambetta,[1] Easwar Magesan,[1] Srikanth J. Srinivasan,[1] Andrew W. Cross,[1]
David W. Abraham,[1] Nicholas A. Masluk,[1] B. R. Johnson,[2] Colm A. Ryan,[2] and M. Steffen[1]
[1]*IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA*
[2]*Raytheon, BBN Technologies, Cambridge, MA 02138, USA*

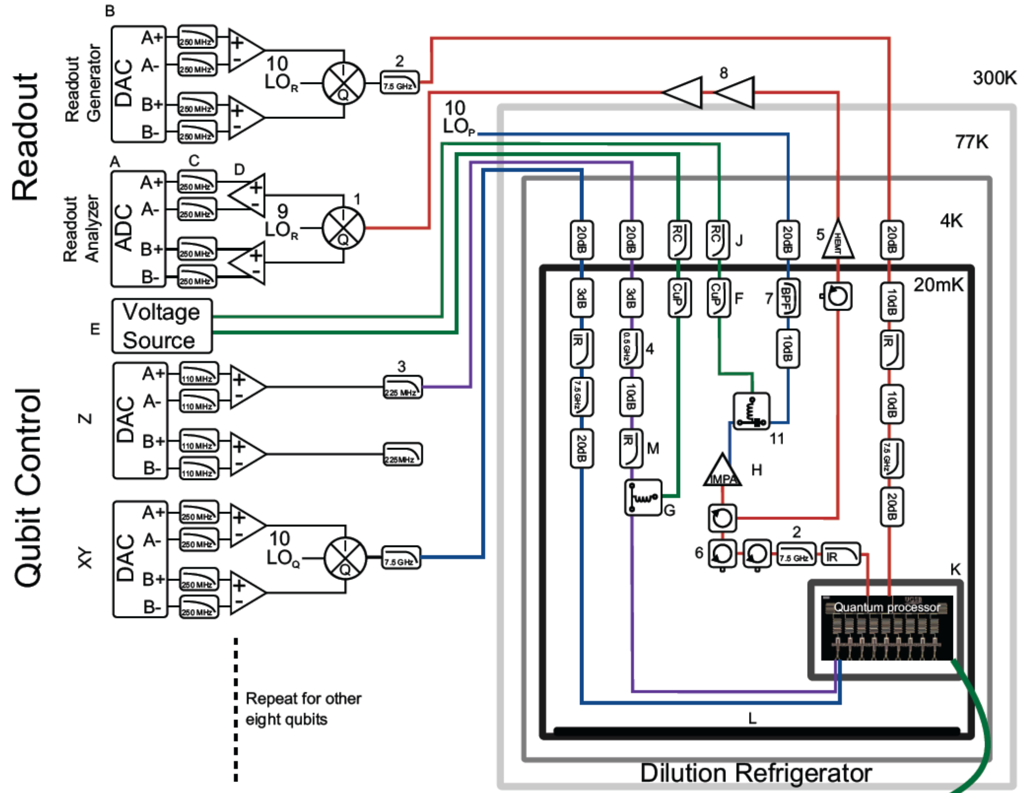
(Dated: 26th November 2013)



Data Figure 1. **Detailed schematic of experimental setup.** Wiring scheme for all room tempera

4 per qubit?

Santa Barbara/Google – circulators and isolators



	Commercial
1	Marki IQ-0307
2	Marki FLP-0750
3	Mini Circuits VLFX-225
4	Mini Circuits VLFX-500
5	Low Noise Factory LNC4_8A
6	QuinStar CTH1392KS
7	Marki FB-1310
8	Miteq AFS3-0010200-22-10P-4
9	Hittite HMC-T2100
10	Anritsu MG3692C
11	Sigatek SB11D2

	Custom
A	Analog to Digital Converter (ADC)
B	Digital to Analog Converter (DAC)
C	Gaussian Filter
D	Differential Amplifier
E	Voltage source ("Fastbias Card")
F	Copper powder & light tight LPF
G	DC Bias T
H	Parametric Amplifier (IMPA)
J	1.5k cold resistor
K	Magnetic Shield
L	"IR-black" coating
M	Light tight LPF

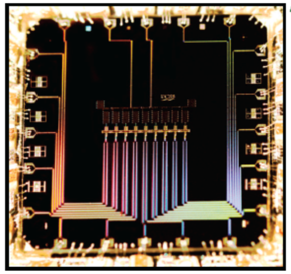
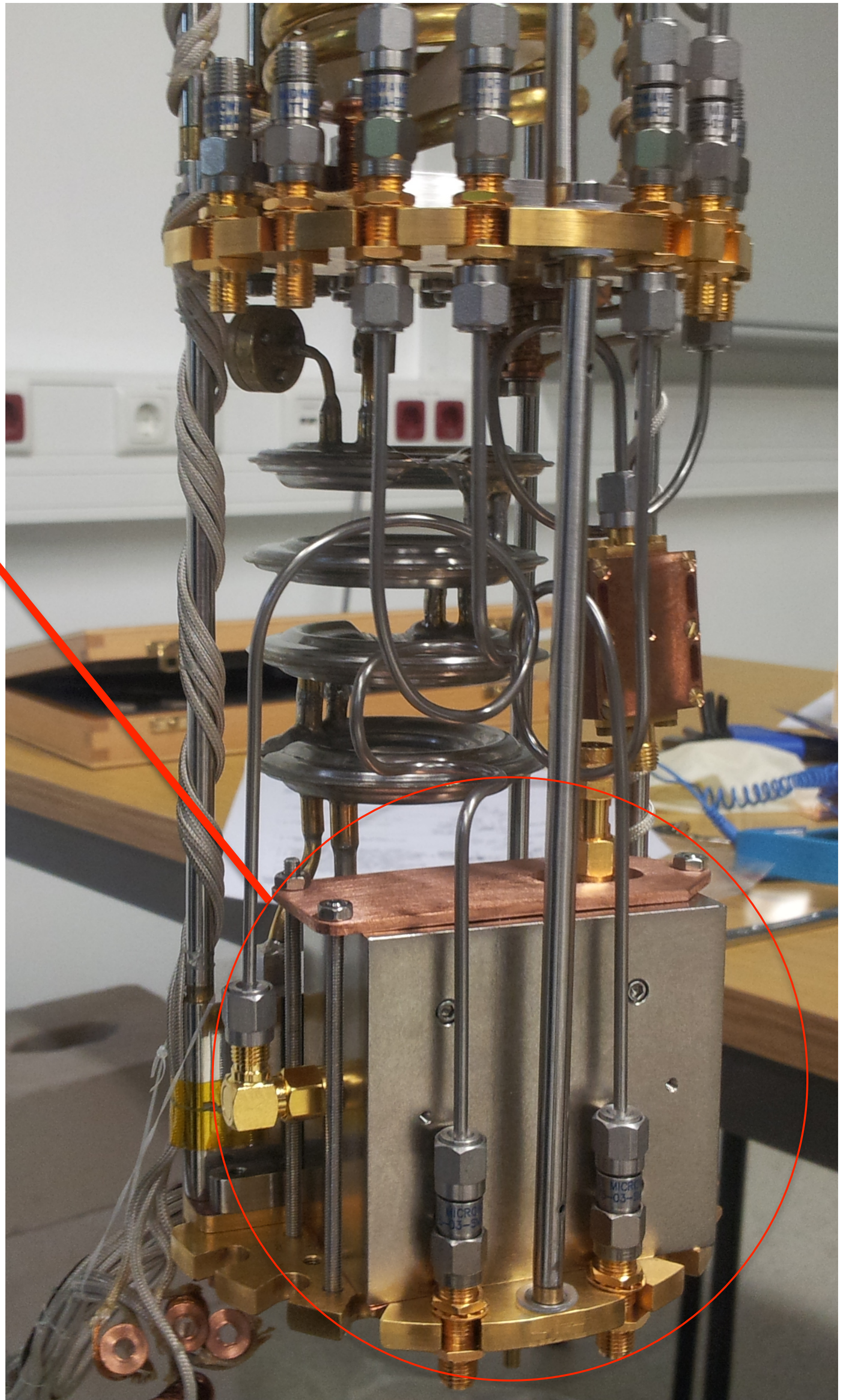


FIG. S29. **Electronics and Control Wiring.** Diagram detailing all of the control electronics, control wiring, and filtering for the experimental

The circulator
 in action (thanks to
Rob McNeil)

It is huge compared
With the qubit!

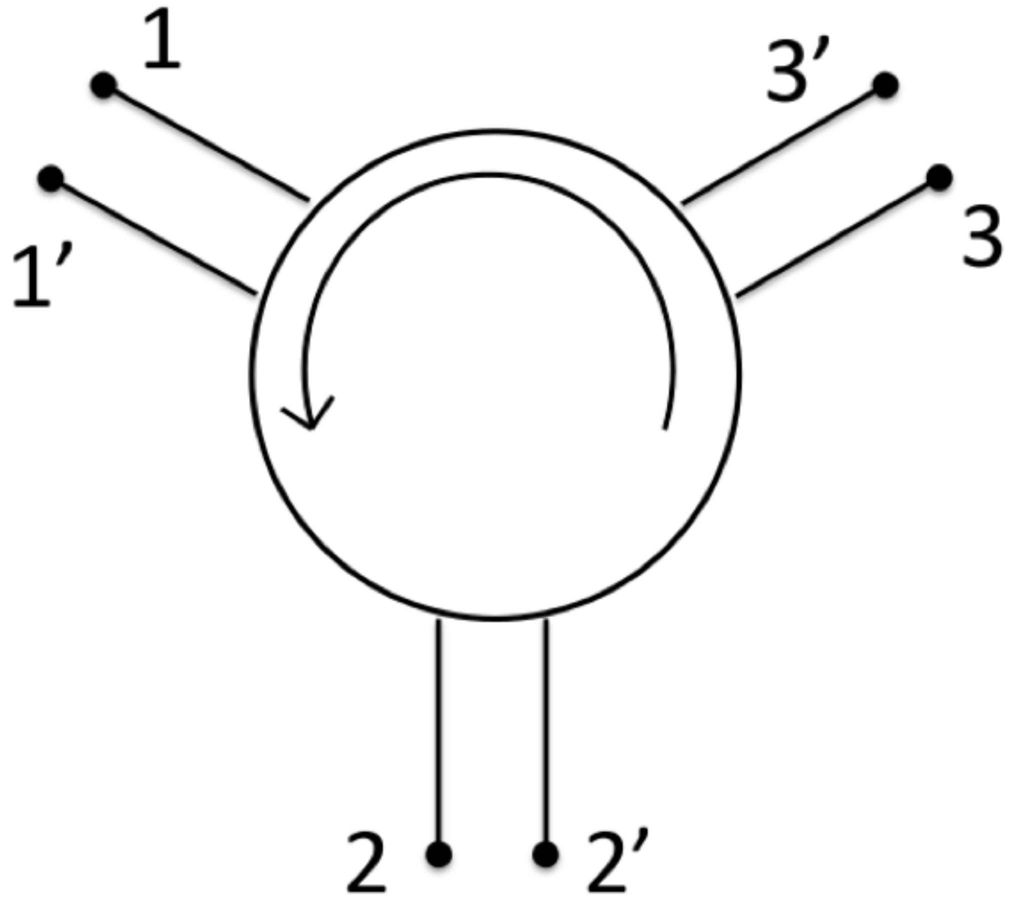
Why? Its physical
size is set by the
wavelength of the
c. 300MHz radiation
that is used in this
application.



Bluhm group
RWTH Aachen

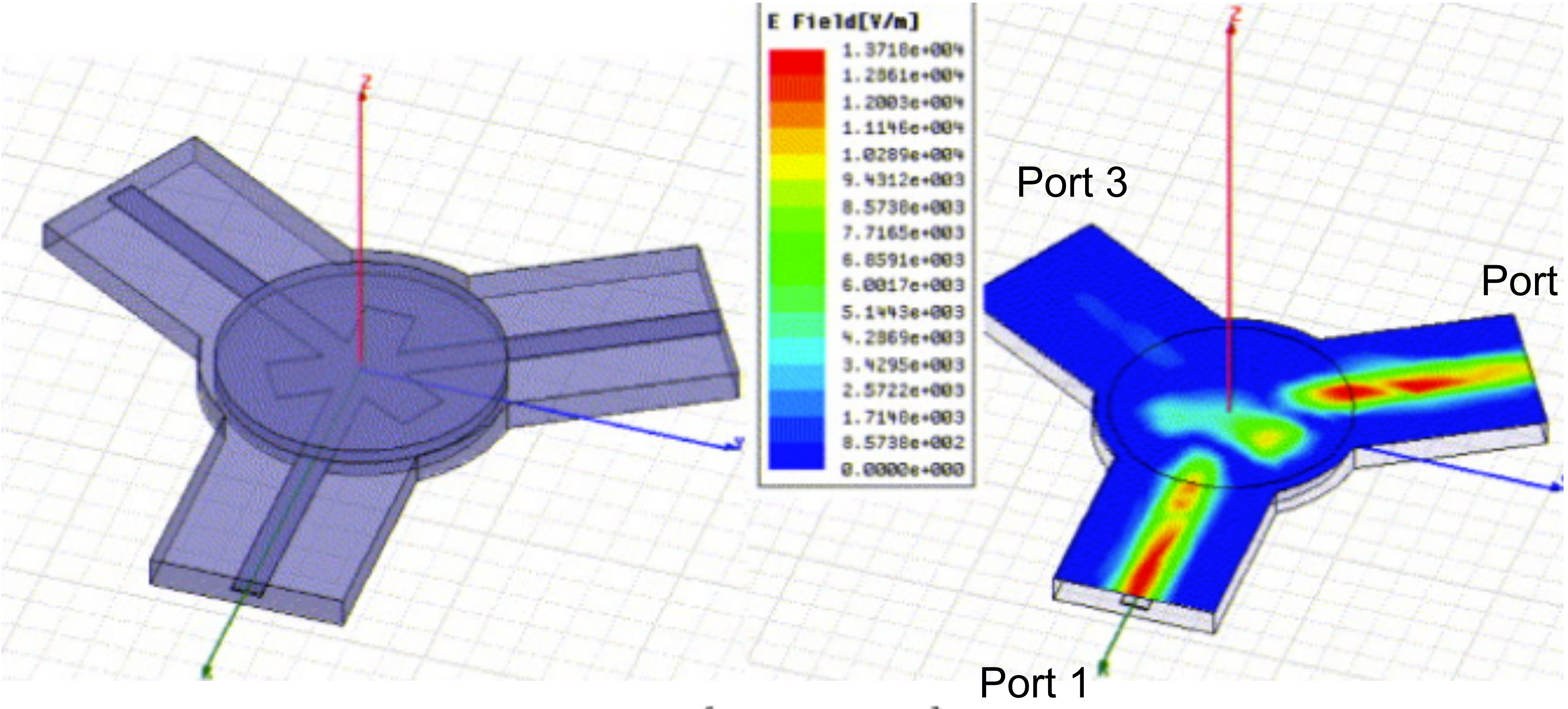
The circulator. (6 terminal device)
What goes on inside?

$$S = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$



Isolator: put 50-Ohm
Resistor across 3-3'

Principle of operation:
Radiation entering one port undergoes Faraday rotation in a piece of ferrite. Interference causes radiation to exit only in right-hand port.



Nonreciprocal Scattering matrix:

$$S = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

Available in bands down to c. 100MHz. Gets very large at lower frequencies.

SURF III
Synchrotron

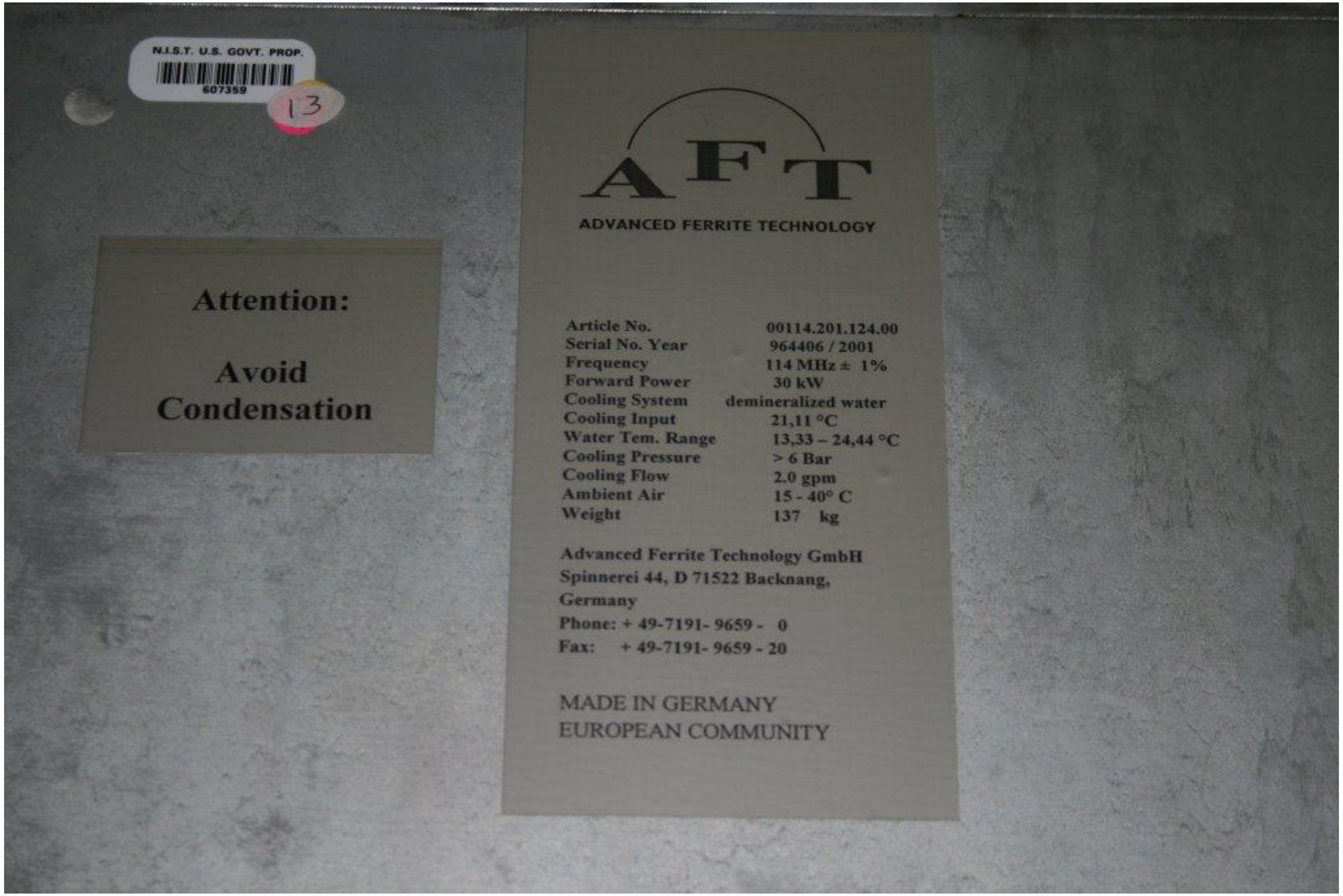
rf high power
Circulator

100 MHz

50cm dimension

(thanks to
Ed Hagley, NIST)


Attention:
Avoid Condensation
Waterload


N.I.S.T. U.S. GOVT. PROP.
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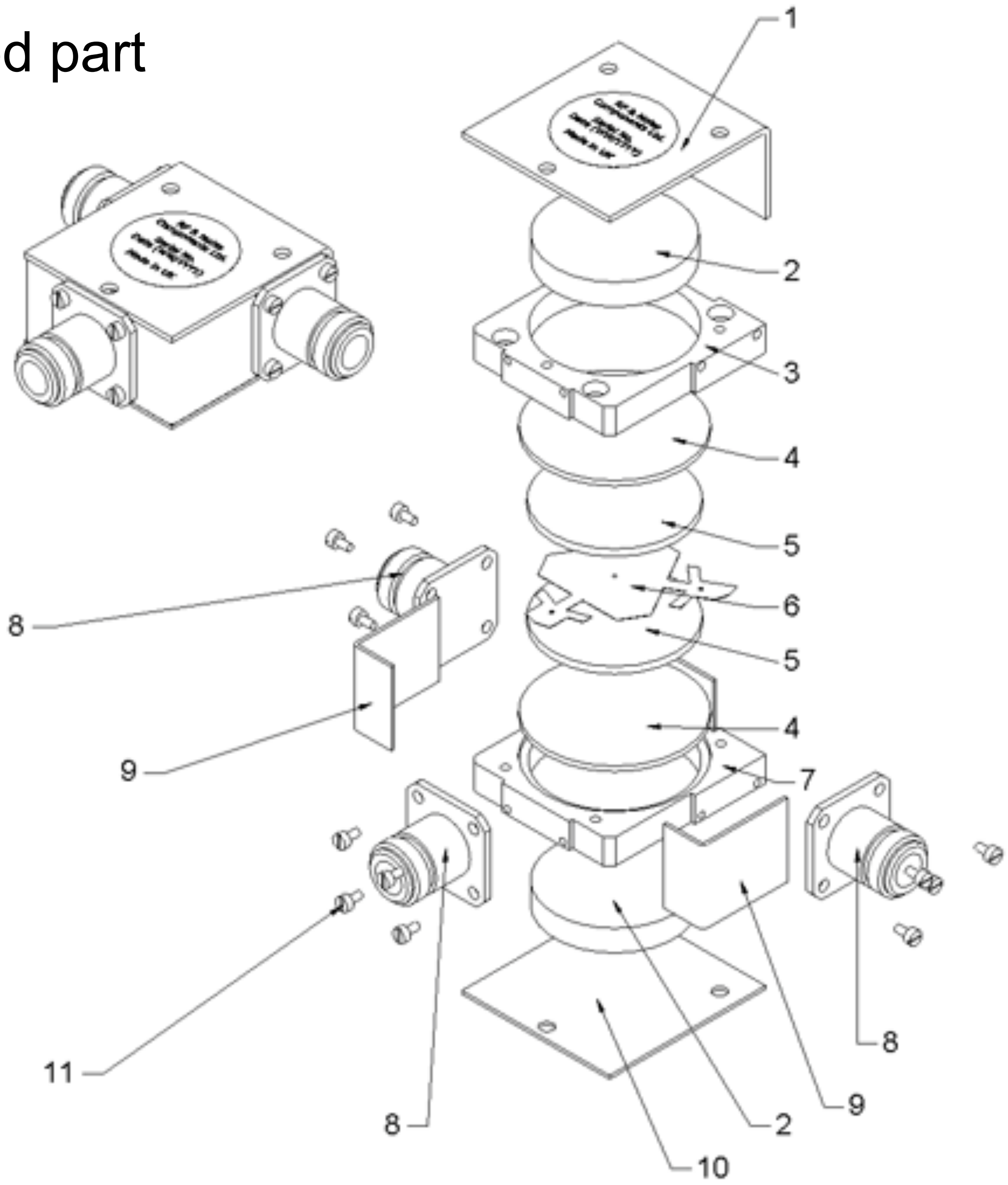
Attention:
Avoid Condensation
AFT
ADVANCED FERRITE TECHNOLOGY
Article No. 00114.201.124.00
Serial No. Year 964406 / 2001
Frequency 114 MHz ± 1%
Forward Power 30 kW
Cooling System demineralized water
Cooling Input 21,11 °C
Water Tem. Range 13,33 – 24,44 °C
Cooling Pressure > 6 Bar
Cooling Flow 2.0 gpm
Ambient Air 15 - 40° C
Weight 137 kg
Advanced Ferrite Technology GmbH
Spinnerei 44, D 71522 Backnang,
Germany
Phone: + 49-7191- 9659 - 0
Fax: + 49-7191- 9659 - 20
MADE IN GERMANY
EUROPEAN COMMUNITY

Microwave Circulator:
A complex, engineered part

Basically unchanged
Since c. 1960.



The concept of the circulator was first started by:

VOLUME XXXI JANUARY 1952 NUMBER 1

Bell Systems Technical Journal

The Ferromagnetic Faraday Effect at Microwave Frequencies and its Applications

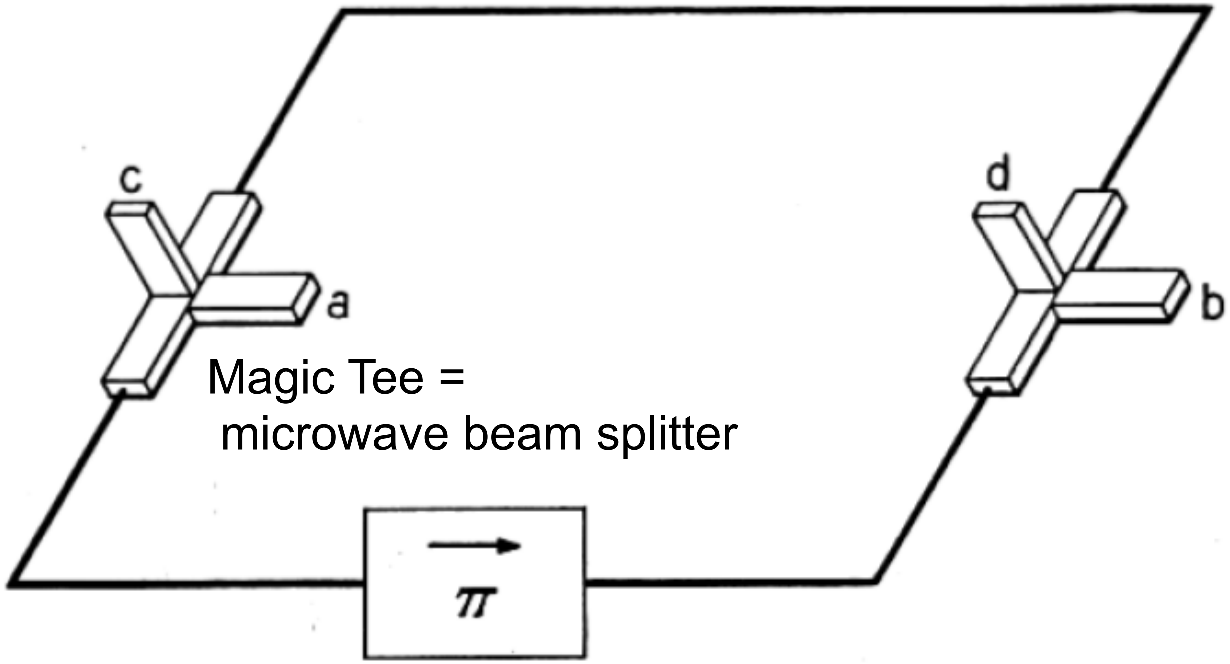
The Microwave Gyrator

BY C. L. HOGAN

But the focus of this paper is something else!

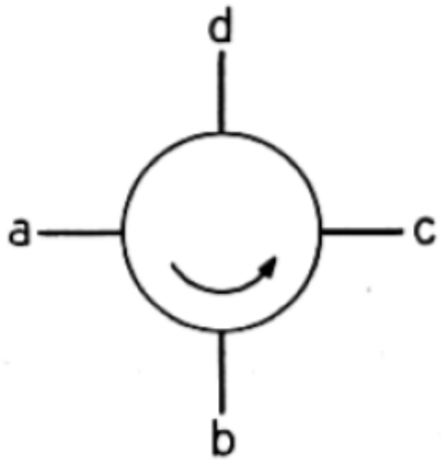
C. L. Hogan, 1978, http://ethw.org/James_H._Mulligan

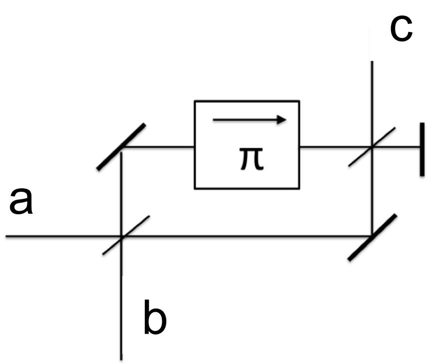
Circulator as a Mach-Zehnder interferometer



CIRCULATOR

Fig. 14—Schematic diagram of circulator.





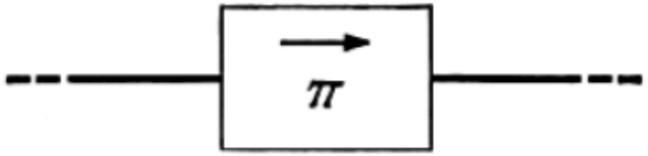
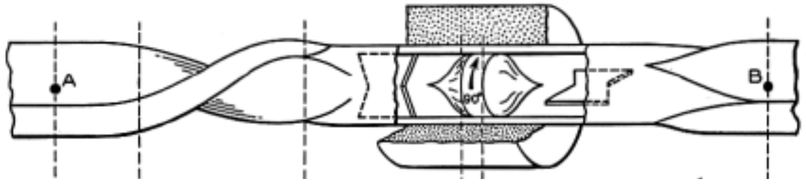


Fig. 12—Circuit symbol for gyrator.



Hogan's gyrator:

Ferrite -- must be wavelength size

One-wave
Pi phase-shifter

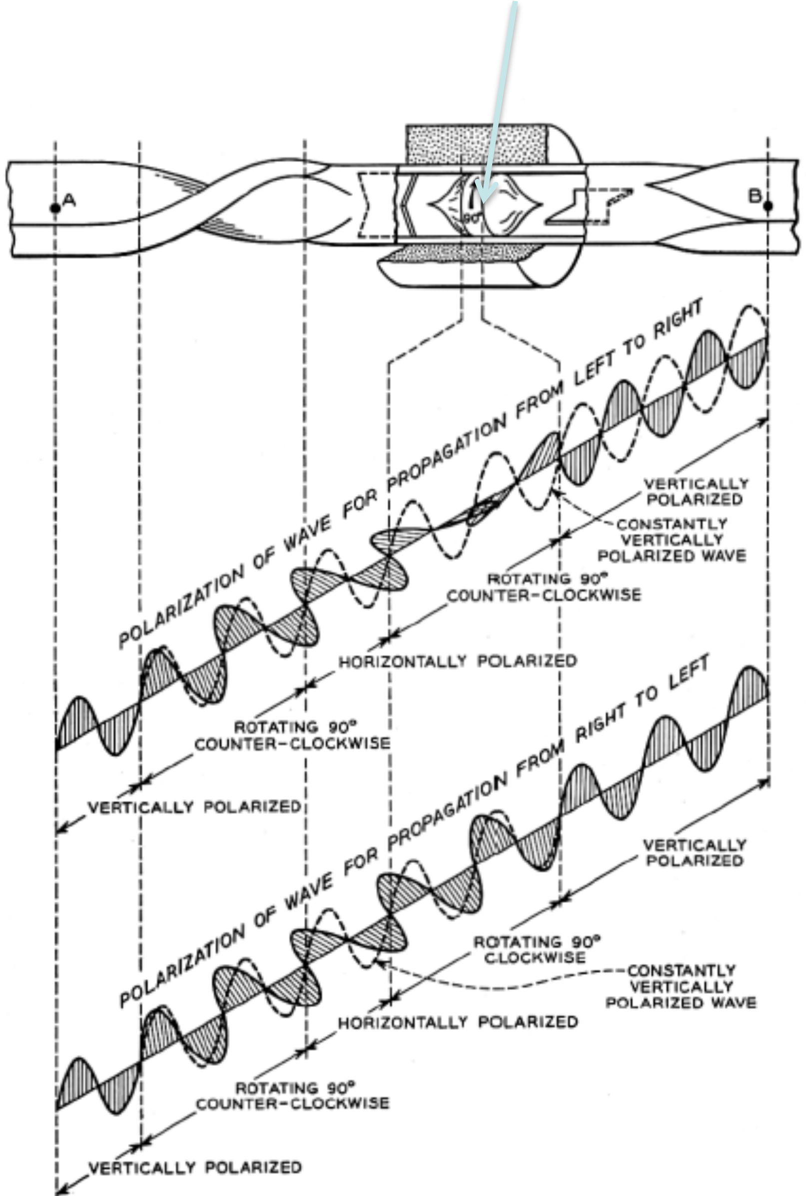


Fig. 11—The microwave gyrator with diagrams which help to explain its operation.

Who invented the Gyrator?

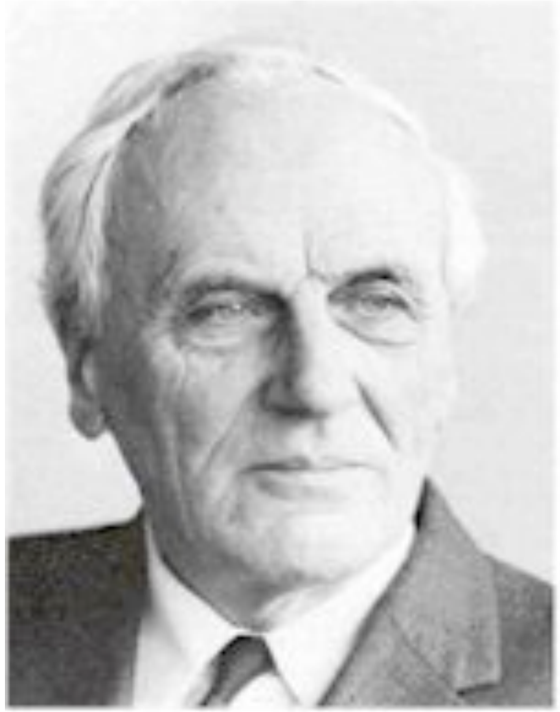
Philips Res. Rept., **3**, 81–101 (Apr. 1948)

THE GYRATOR, A NEW ELECTRIC NETWORK ELEMENT

by B. D. H. TELLEGEN

Summary

Besides the capacitor, the resistor, the inductor, and the ideal transformer a fifth, linear, constant, passive network element is conceivable which violates the reciprocity relation and which is defined by (10). We have denoted it by the name of "ideal gyrator". By its introduction the system of network elements is completed and network synthesis is much simplified. The gyrator can be realized by means of a medium consisting of particles carrying both permanent electric and permanent magnetic dipoles or by means of a gyromagnetic effect of a ferromagnetic medium.



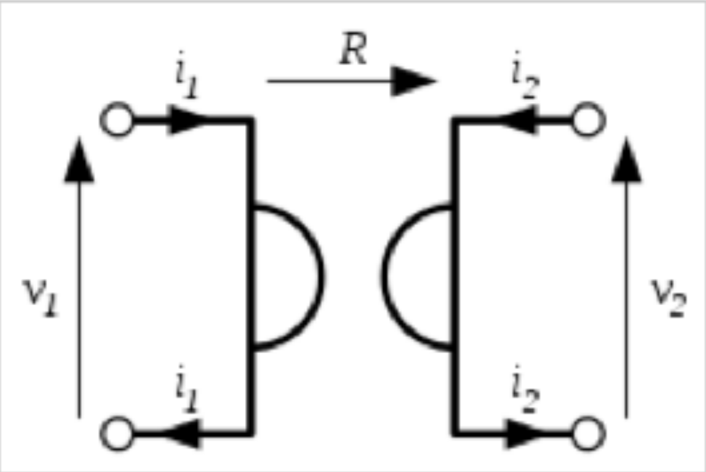
Bernard D. H. Tellegen
Phillips Research

- Pure theory concept, introduced nonreciprocity into electric circuit theory
- Faraday rotation is only partial realization of what Tellegen had in mind!

Basic equations of Tellegen's gyrator:

$$v_2 = Ri_1$$
$$v_1 = -Ri_2$$

- Phase reversal idea, but
- Permitted at all wavelengths (basic energy conservation arguments)
- i.e., could be much smaller than wavelength
- Thus, circulator could be arbitrarily smaller than wavelength



Gyrator schematic labelled

$$Z = \begin{bmatrix} 0 & -R \\ R & 0 \end{bmatrix}$$

$$S = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

How Tellegen got the idea – from the original patent

Non-reciprocal dielectric response of the ionosphere

C. D. 621.392.5

Auteursrecht voorbehouden.

OCTROOIRAAD

NEDERLAND

Uitvinder: Prof. Ir BERNARDUS DOMINICUS HUBERTUS TELLEGEN, te Eindhoven.

OCTROOI No. 68724.

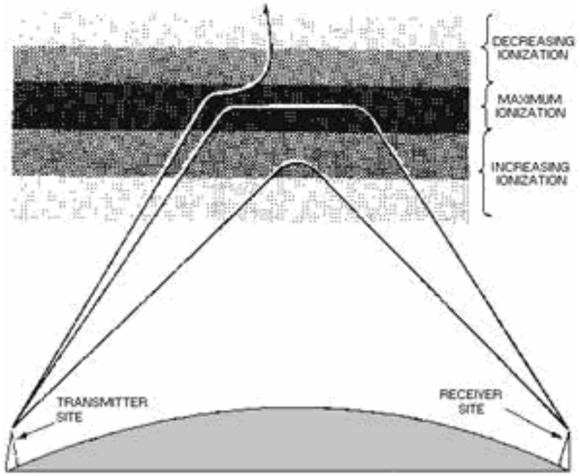
KLASSE 95 g (95 g 4 b 1 b).

N.V. PHILIPS' GLOEILAMPENFABRIEKEN, te Eindhoven.

Passieve electrische vierpool, waarvoor het reciprociteitstheorema niet geldt, en schakeling met deze vierpool.

Aanvrage No. **131903** Ned., ingediend 29 April 1947, 24 uur; openbaar gemaakt 15 December 1950.

Ook is het bekend, dat somtijds een zend- en een ontvangantenne tezamen zulk een vierpool vormen, daar gebleken is (zie Proc. Inst. Rad. Eng. 16, 1928, blz. 514 en 515), dat, wanneer men de ionosfeer als een diëlectrische homogeen doch anisotroop medium opvat, de aan dit medium toe te kennen diëlectriciteitsmatrix niet symmetrisch behoeft te zijn.



Tellegen’s patented device concepts

- Engineered materials with cross electric/magnetic responses
- Coupling to material by coils or plates
- Never implemented
    - Known in magnetoelectrics
    - Another Bell Labs story…

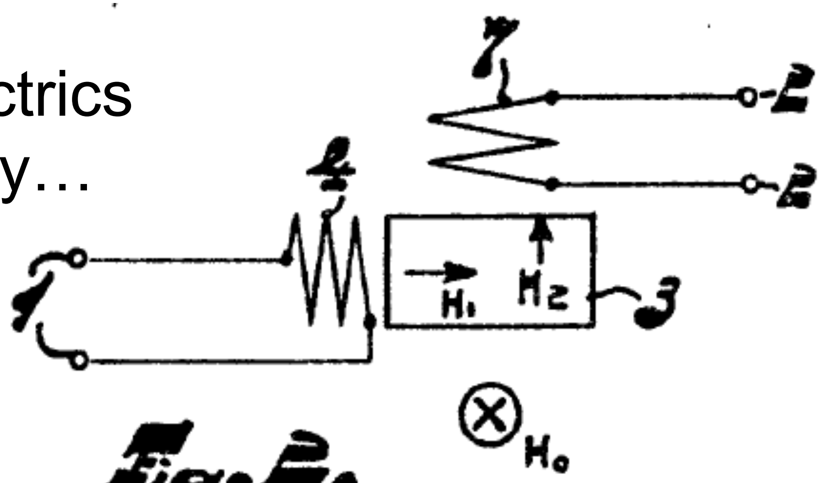


Fig. 2.

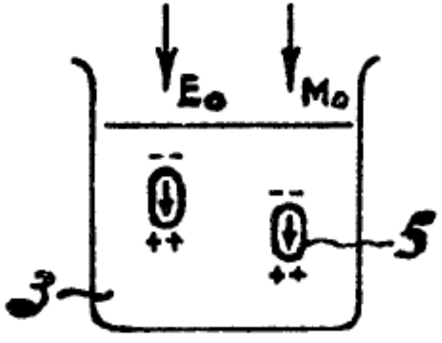


Fig. 3a.

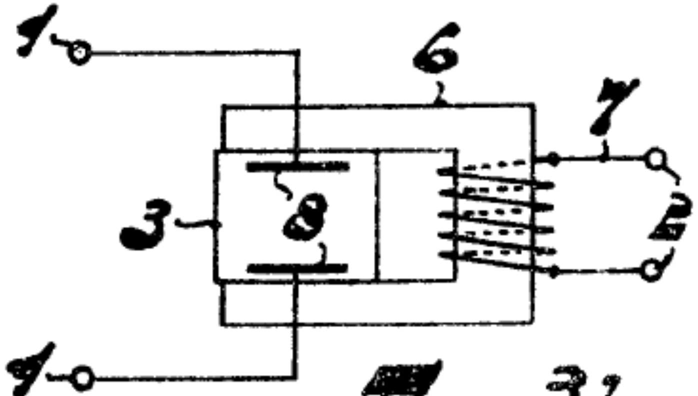


Fig. 3b.

"Resistive gyrator" or "germanium gyrator"

- Another Bell Labs project – Mason, [Shockley],…
- Nonreciprocal resistive phenom.: Hall effect
- Galvanic contact, rather than reactive [not Tellegen]

JOURNAL OF APPLIED PHYSICS VOLUME 24, NUMBER 2 FEBRUARY, 1953

Hall Effect Modulators and "Gyrators" Employing Magnetic Field Independent Orientations in Germanium

W. P. MASON, W. H. HEWITT, AND R. F. WICK
Bell Telephone Laboratories, Murray Hill, New Jersey

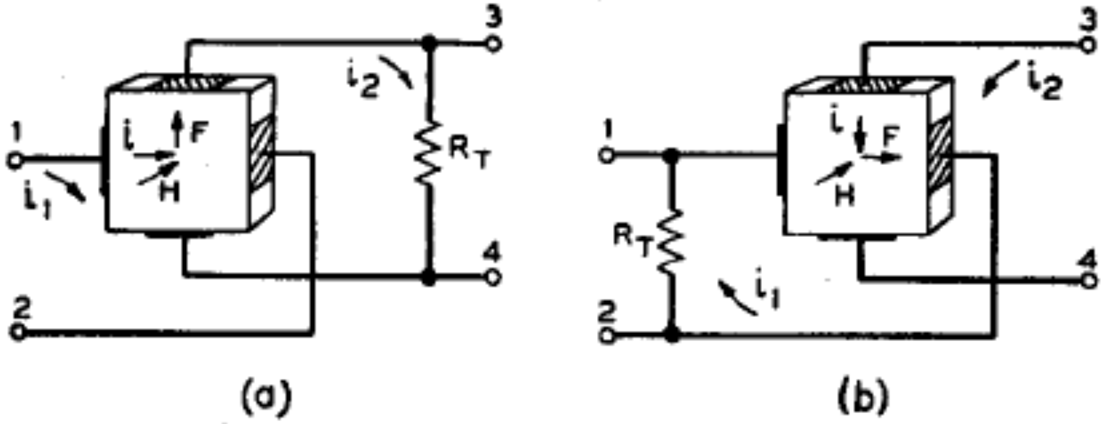


FIG. 4. Figure showing the nonreciprocal nature of Hall effect transmission.

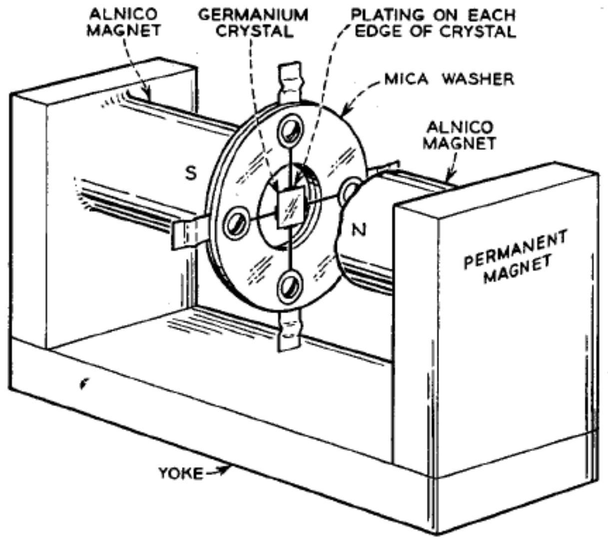
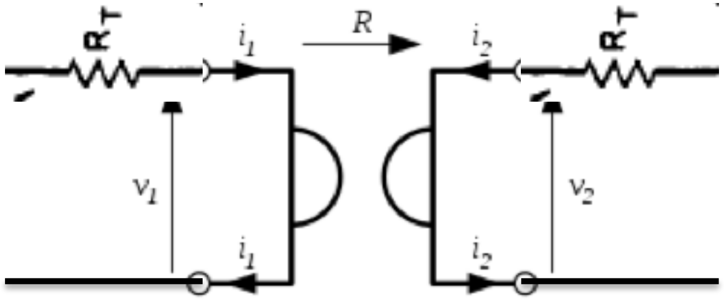


FIG. 6. Drawing of "gyrator."

Resistive gyrator was a failure (unlike Faraday gyrator)

- Wick, 1954, proved that gyrator has intrinsic contact resistance
- Applies also to quantum Hall effect
    - Irreducible two-terminal resistance



No more history. But can we try something new?

JOURNAL OF APPLIED PHYSICS VOLUME 25, NUMBER 6 JUNE, 1954

Solution of the Field Problem of the Germanium Gyrator

R. F. Wick
Bell Telephone Laboratories, Murray Hill, New Jersey

3. A LOWER LIMIT TO THE TRANSMISSION LOSS IN A RESISTANCE GYRATOR

The above result can be used to derive a lower limit to the insertion loss in a resistance gyrator which we will

$$V_a = i_1 Z_{aa} + i_2 Z_{ba}, \quad V_b = -i_1 Z_{ba} + i_2 Z_{bb}. \qquad (5)$$

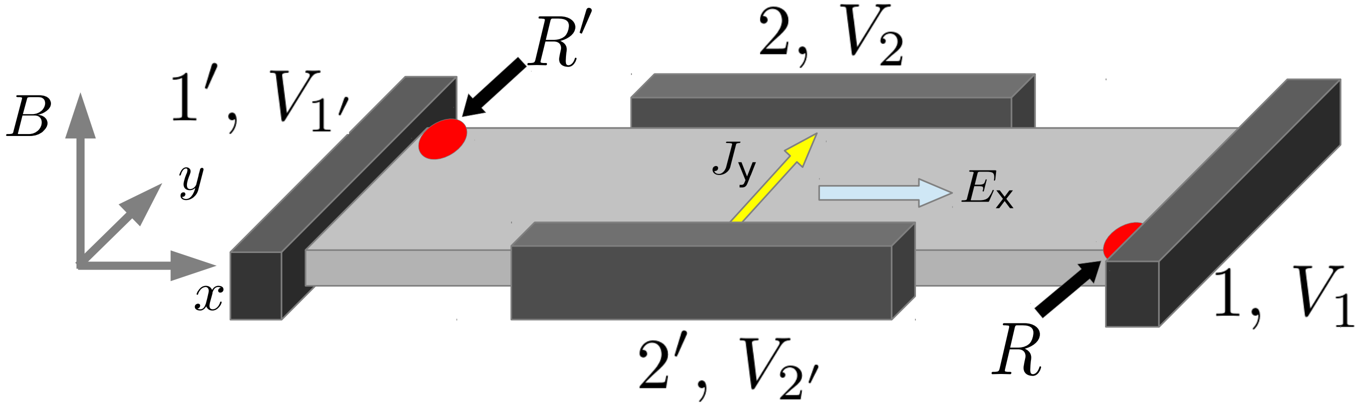
The insertion loss between resistances equal to the respective image impedances is given by

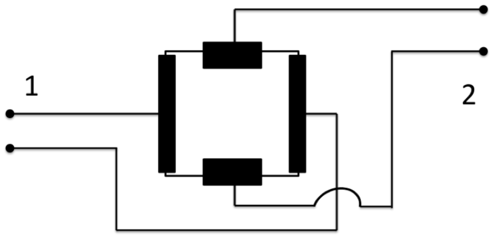
$$20 \log_{10} \left| \frac{2}{Z_{ba}/Z_{aa} + Z_{ba}/Z_{bb}} \left[1 + \left(1 + \frac{Z_{ba}^2}{Z_{aa} Z_{bb}} \right)^{\frac{1}{2}} \right] \right|. \qquad (6)$$

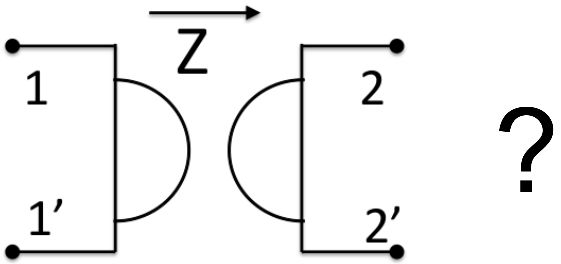
But Z_{ba}/Z_{aa} is the open circuit voltage across terminals 2–4 per unit voltage applied to terminal 1–3, and so cannot exceed 1. Similarly Z_{ba}/Z_{bb} cannot exceed 1. It follows from (6) that the lowest loss is 7.66 db, obtained when $Z_{aa} = Z_{bb} = Z_{ba}$.

Lossiness of the “resistive gyrator”

- dissipation concentrated at edge contact “hot spots”

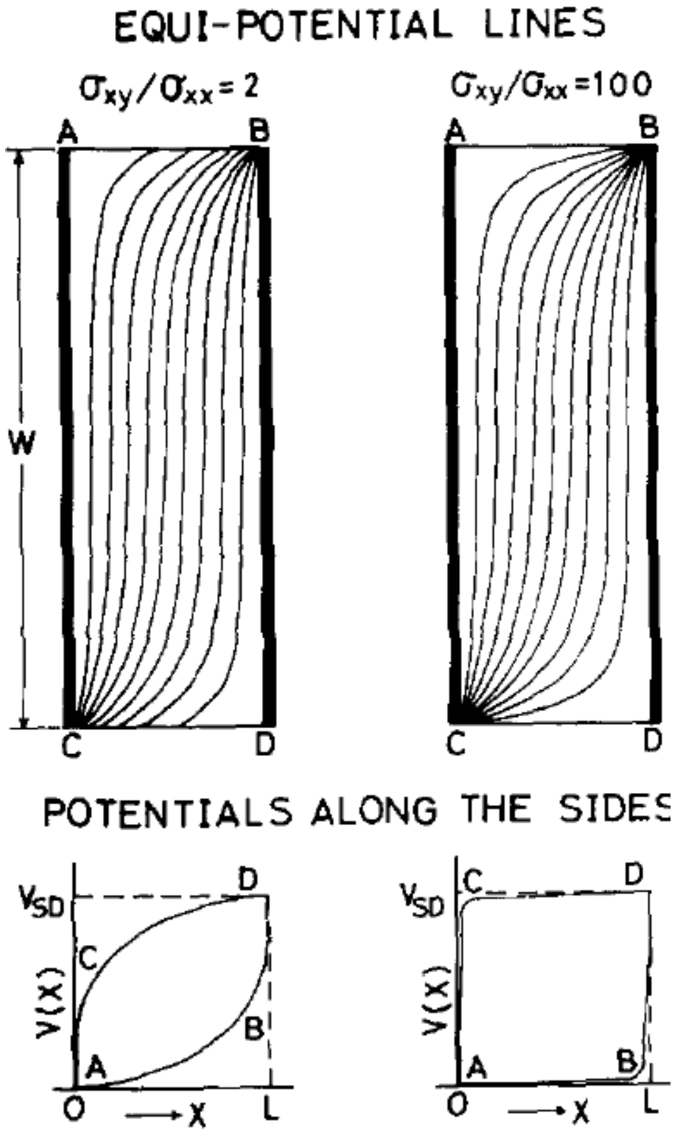






Edge contact resistance is not a quantum transport phenomenon

-- already understood in the Drude-Ohm-Hall picture



Kawaji 1978

The Hall Effect Circulator

Outline

- Current growing role of circulators in qubit experiments
- What is a circulator, and what is a gyrator?
- Faraday effect (bulky) vs. Hall effect – some history
- Hall as failure (1953)
- Our new work – capacitive vs. ohmic/galvanic contact
- Neat classical theory: 1+1 Dirac equation, chiral edge magnetoplasmons
- Conditions for new gyrators & circulators
- Experimental conditions
- What about quantum?

G. Viola and D. P. DiVincenzo, *Hall Effect Gyrators and Circulators,* Phys. Rev. X **4**, 021019 (2014).

arXiv.org > cond-mat > arXiv:1312.5190

Condensed Matter > Mesoscale and Nanoscale Physics

Hall Effect Gyrators and Circulators

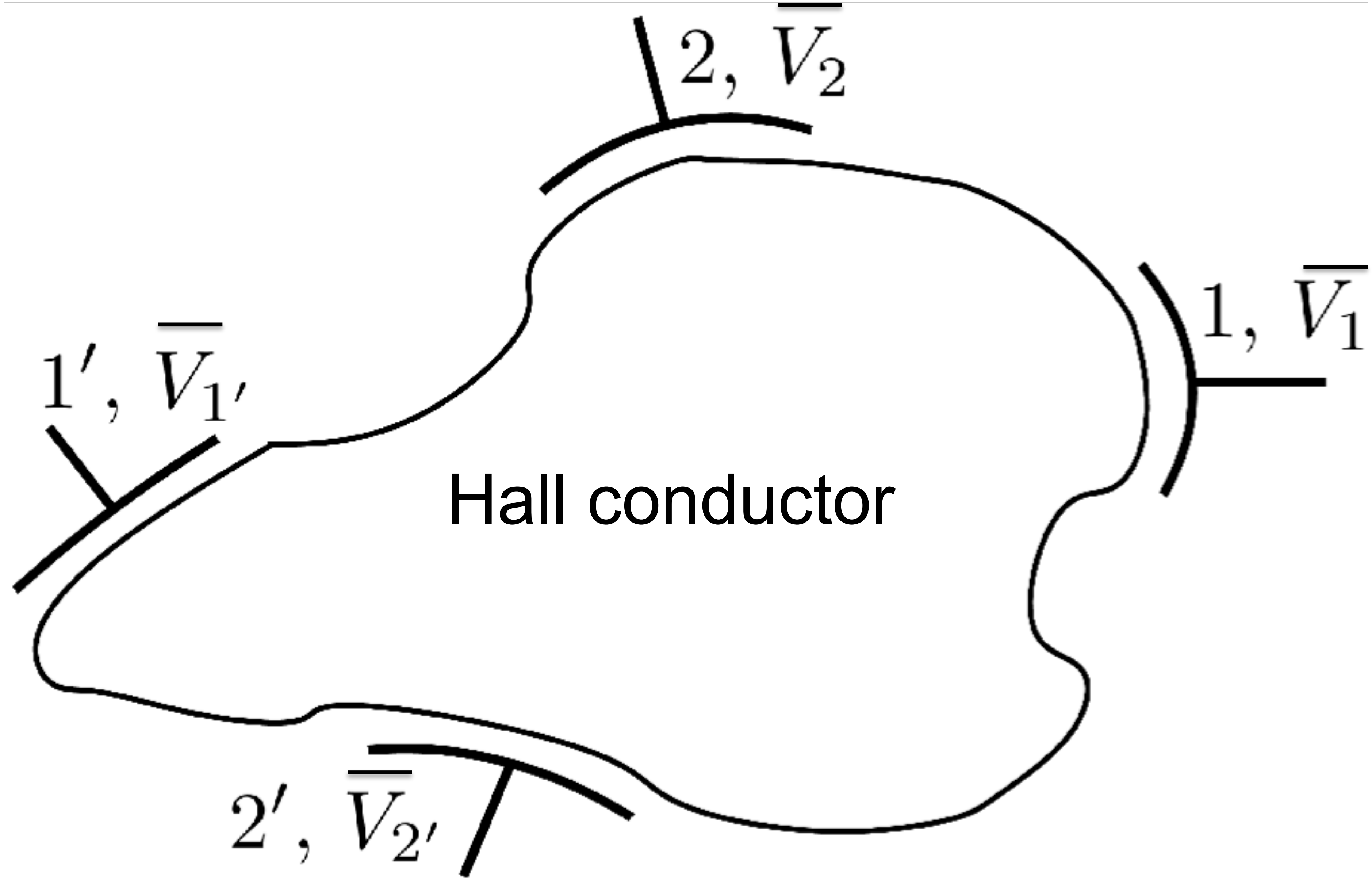
Giovanni Viola, David P. DiVincenzo

(Submitted on 18 Dec 2013)

G. Viola and D. P. DiVincenzo,
Hall Effect Gyrators and Circulators, Phys. Rev. X **4**, 021019 (2014).

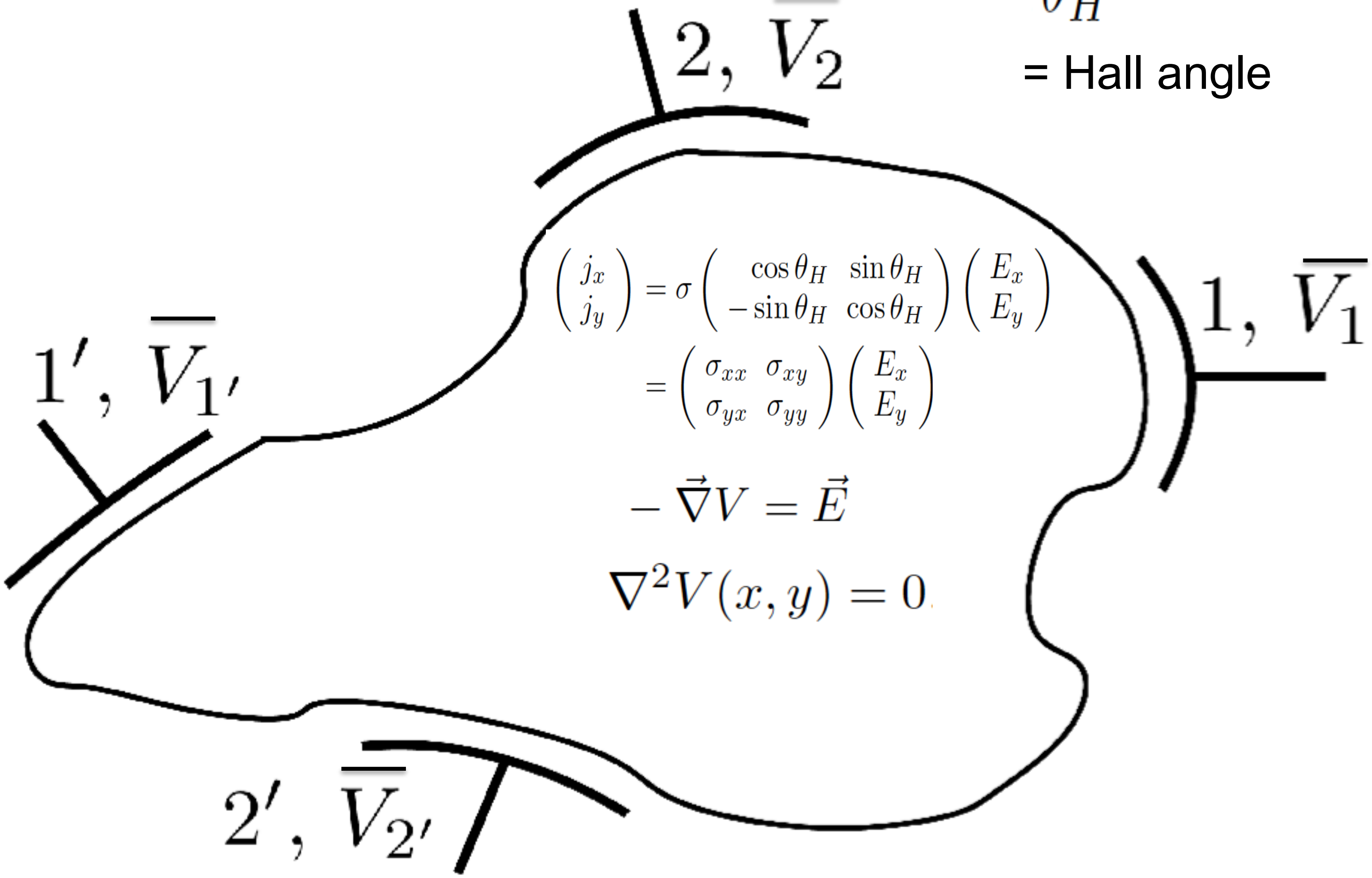
Our idea: Replace ohmic contacts by capacitive contacts

Arbitrary-shaped Hall conductor with four contacts



Classical Ohm-Hall model of 2D conductor (following Wick 1954)

θ_H = Hall angle



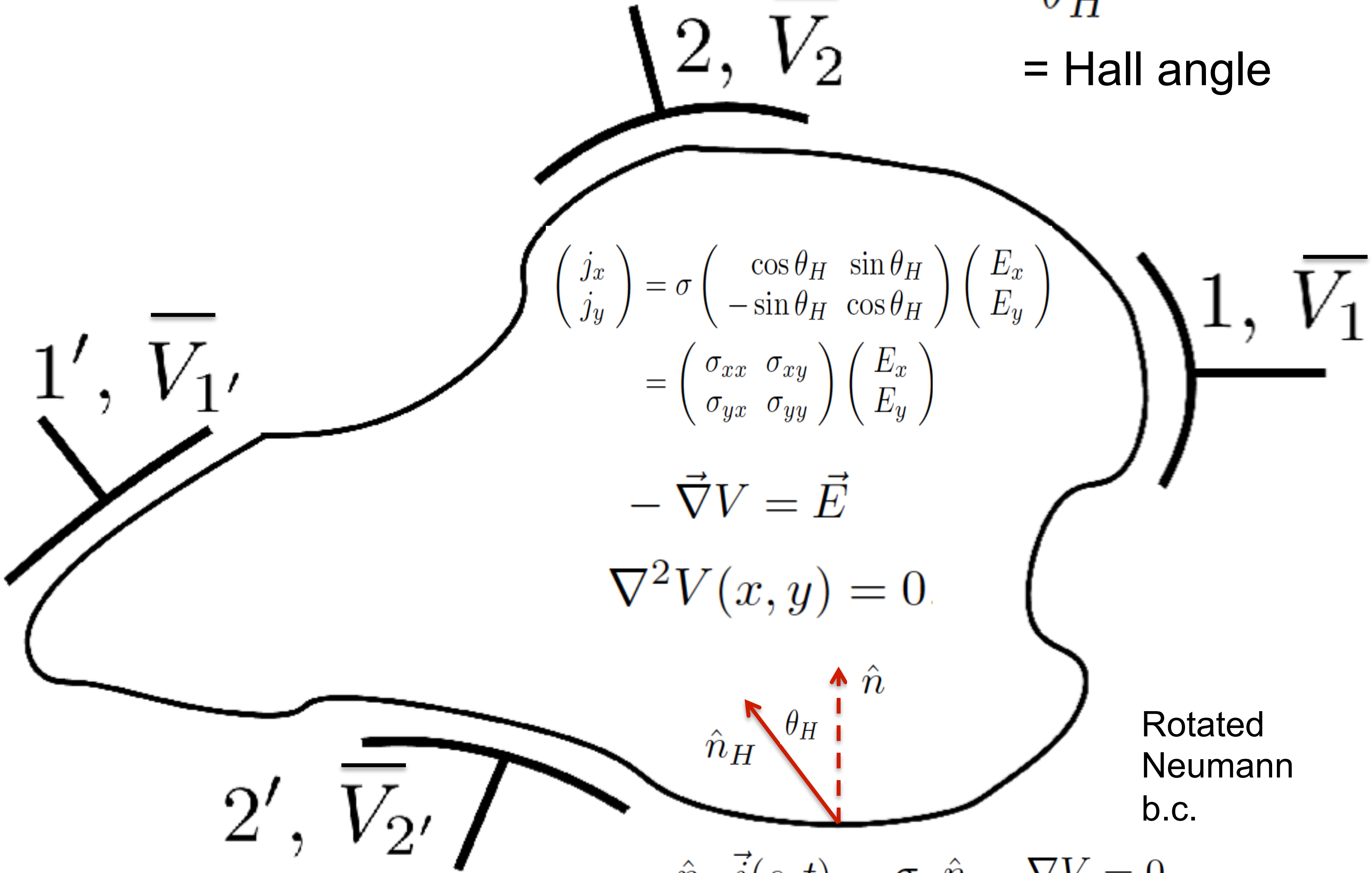
$$\begin{pmatrix} j_x \\ j_y \end{pmatrix} = \sigma \begin{pmatrix} \cos\theta_H & \sin\theta_H \\ -\sin\theta_H & \cos\theta_H \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

$$-\vec{\nabla} V = \vec{E}$$

$$\nabla^2 V(x,y) = 0$$

Boundary conditions of classical transport model (following Wick 1954)

θ_H = Hall angle



$$\begin{pmatrix} j_x \\ j_y \end{pmatrix} = \sigma \begin{pmatrix} \cos\theta_H & \sin\theta_H \\ -\sin\theta_H & \cos\theta_H \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

$$-\vec{\nabla} V = \vec{E}$$

$$\nabla^2 V(x,y) = 0$$

Rotated Neumann b.c.

$$\hat{n} \cdot \vec{j}(s,t) = \sigma \cdot \hat{n}_H \cdot \nabla V = 0$$

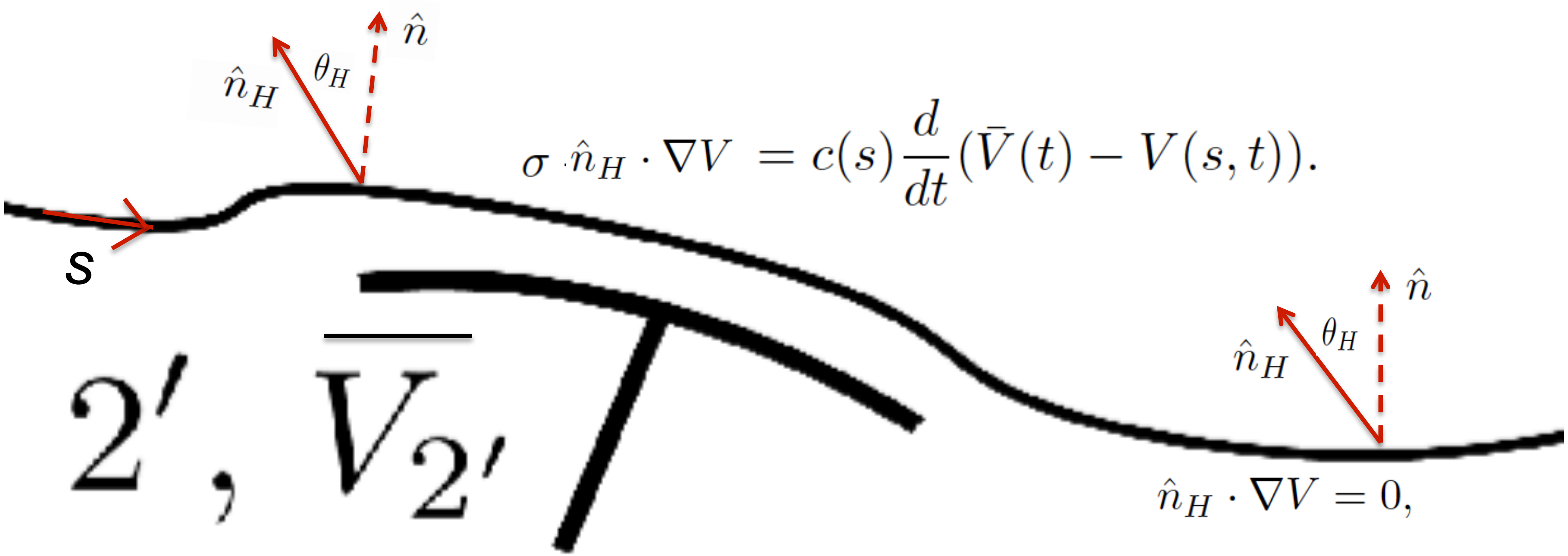
Blowup of boundary at contact

New boundary condition for capacitive contact

θ_H

= Hall angle

$$\nabla^2 V(x, y) = 0$$



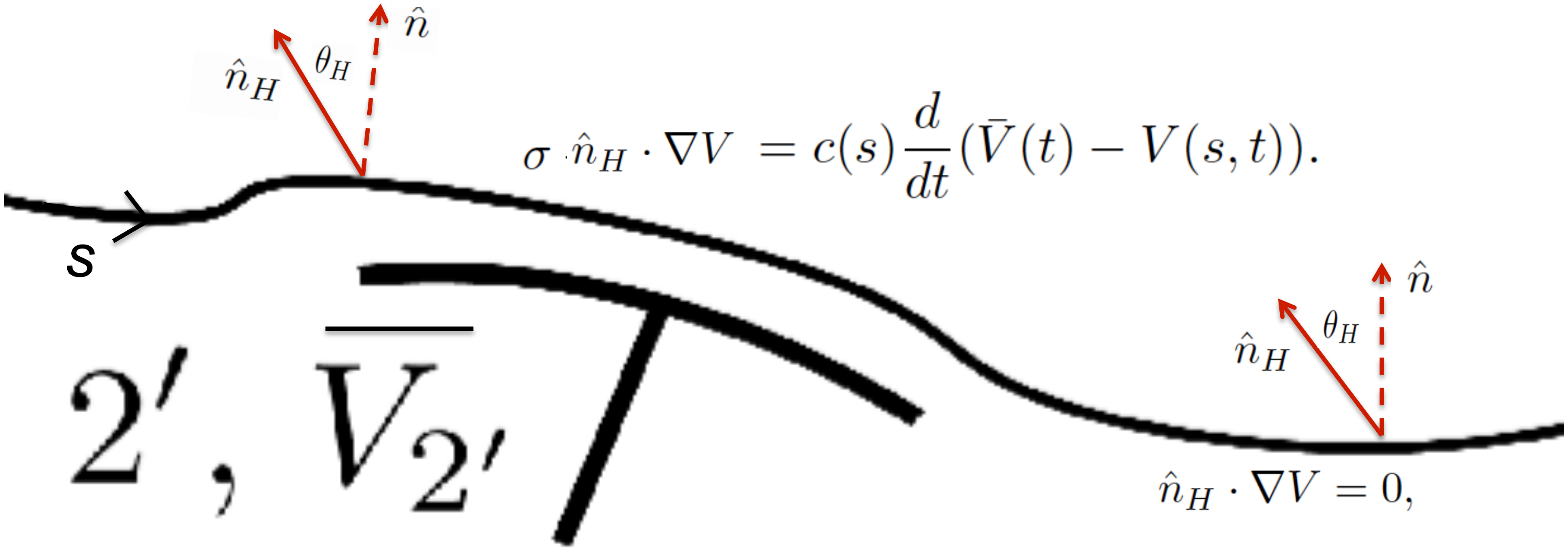
Assume a.c. external potential V2'~cos(ωt)
Fourier transform boundary condition equation

b.c. is
-mixed (cf. Robin)
-inhomogeneous
-skew
-complex-valued

$$\nabla^2 V(x,y) = 0$$

$$-\sigma\, \hat{n}_H \cdot \nabla V(s,\omega) = i\omega c(s)(\bar{V}(\omega) - V(s,\omega)).$$

$$\sigma\, \hat{n}_H \cdot \nabla V = c(s)\frac{d}{dt}(\bar{V}(t) - V(s,t)).$$



$$\hat{n}_H \cdot \nabla V = 0,$$

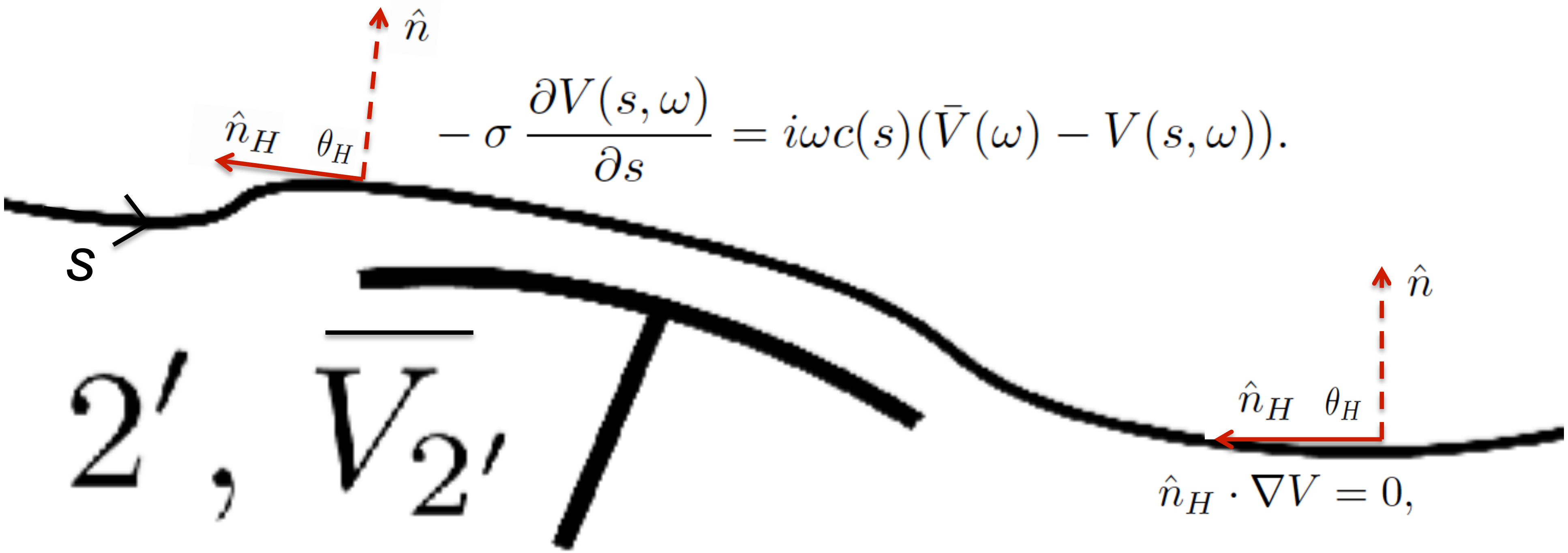
Hall angle -> 90 degrees ("quantum" Hall)

Boundary condition equation becomes

-Ordinary first order equation
-Can be solved without reference to bulk solution
-Response is independent of shape

Interior fields become slave to boundary problem

$$\nabla^2 V(x,y) = 0$$



Homogeneous part of boundary-condition equation is a

1+1 Dirac equation (massless)
$c(s)^{-1}$ is position-dependent velocity

$$-\sigma \frac{\partial V(s,\omega)}{\partial s} = i\omega c(s)(\bar{V}(\omega) - V(s,\omega)).$$

Eigenvalues are equally spaced:

$$\omega_n = \frac{2n\pi\sigma}{\int_0^P c(s)ds}.$$

Interpretation of eigensolutions:

undamped chiral edge magnetoplasmons

Capacitor voltages

V1-V1'=V cos (ωt)

V2 & V2' short-circuited

Hall angle 90 degrees

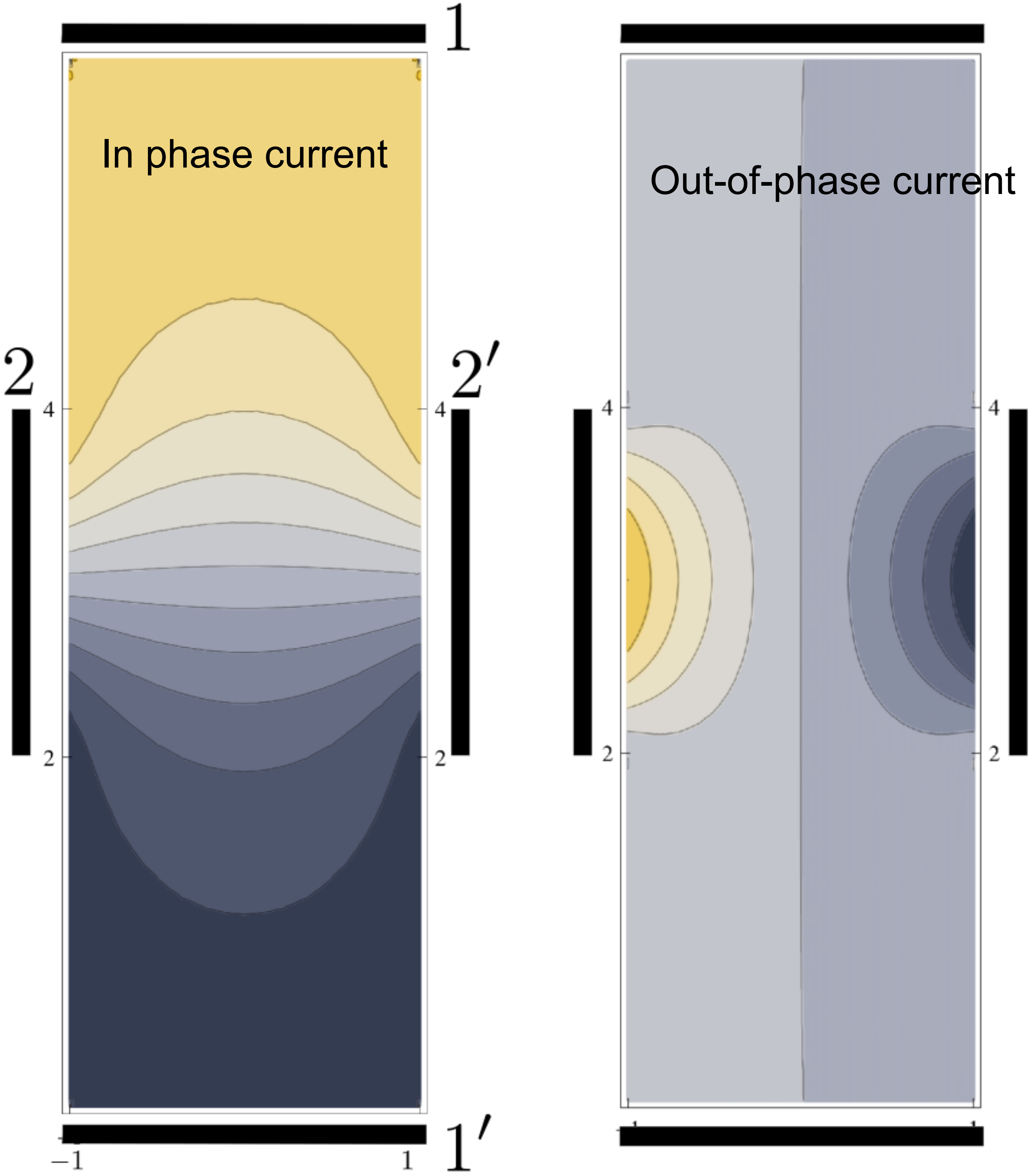
Smooth transverse
Current flow

No longitudinal current
flow

No net out-of-phase current

No dissipation

Perfect gyrator at this
frequency



Frequency dependence of impedance response

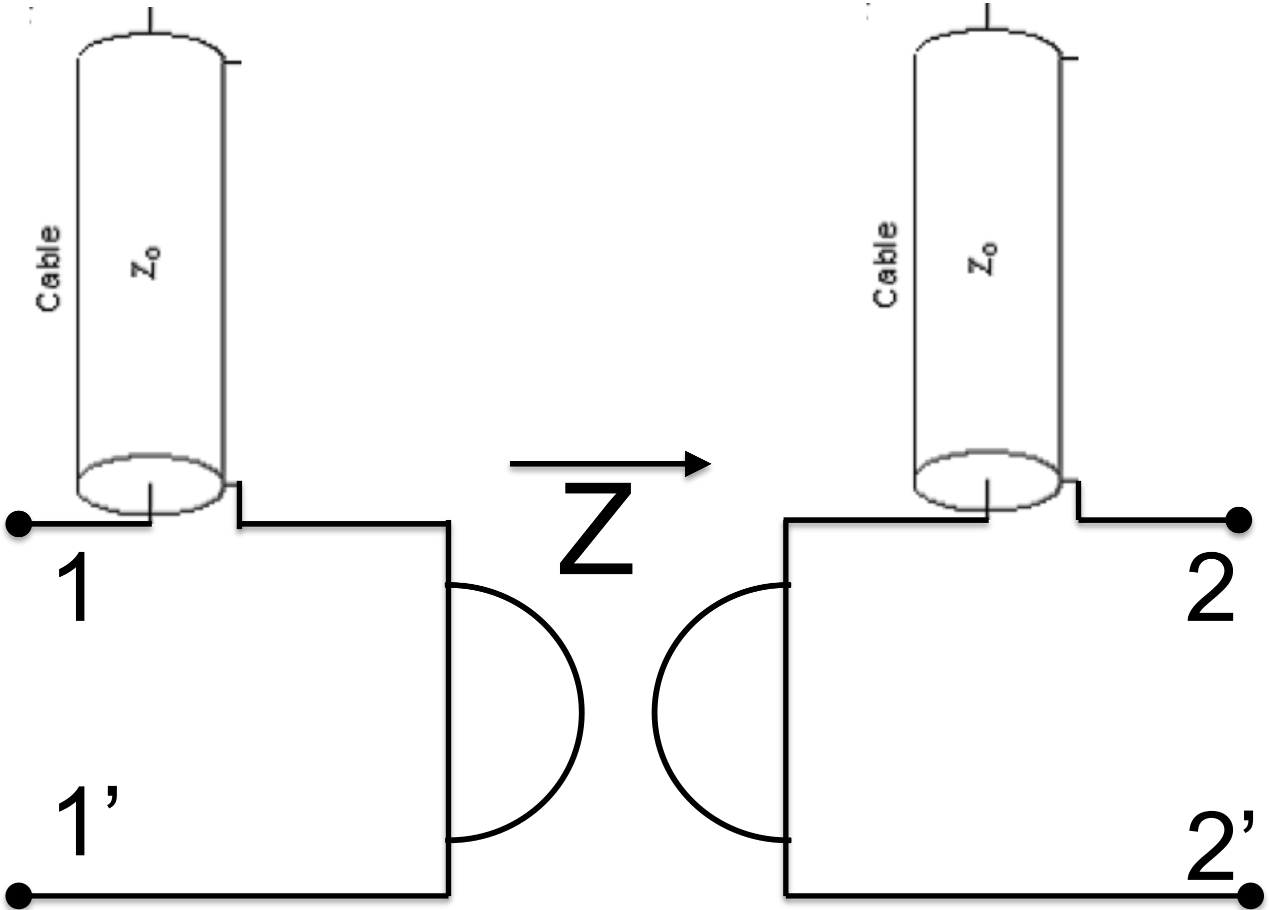
$$Y_{2P}(\omega) = \frac{\sigma}{2}\begin{pmatrix} i\tan\frac{\omega C_L}{\sigma} & -1+\sec\frac{\omega C_L}{\sigma} \\ 1-\sec\frac{\omega C_L}{\sigma} & i\tan\frac{\omega C_L}{\sigma} \end{pmatrix},$$

ch when inverted gives the two-port impedance

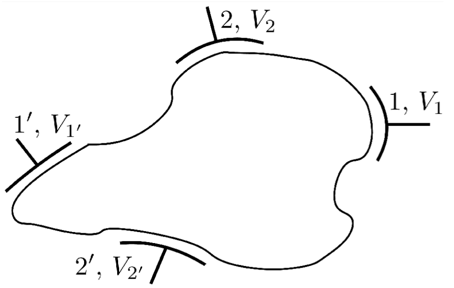
$$Z_{2P}(\omega) = \frac{1}{\sigma}\begin{pmatrix} -i\cot\frac{\omega C_L}{2\sigma} & -1 \\ 1 & -i\cot\frac{\omega C_L}{2\sigma} \end{pmatrix}.$$

Delay-line model

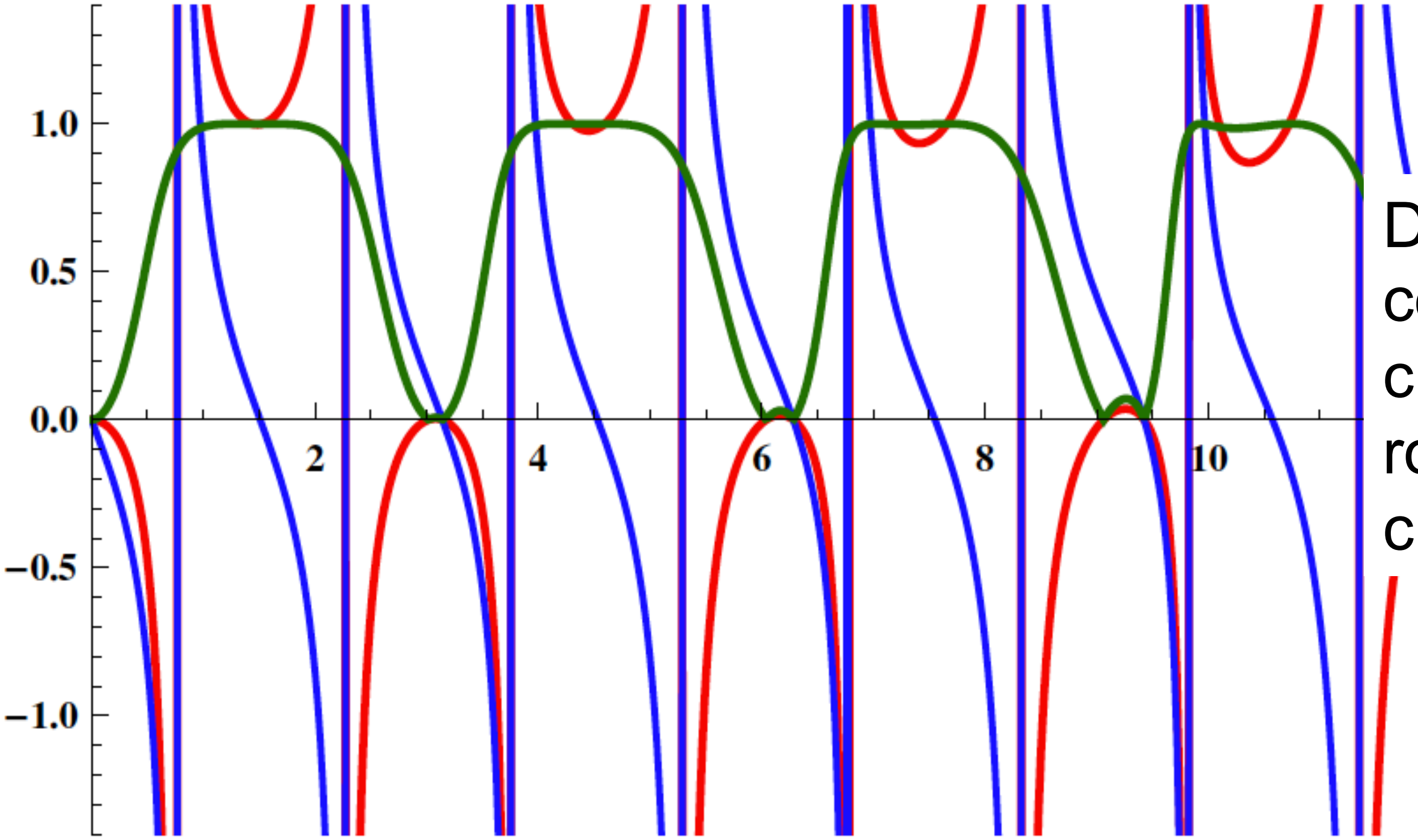
Physically, the delay line is provided by dispersionless edge magnetoplasmon propagation



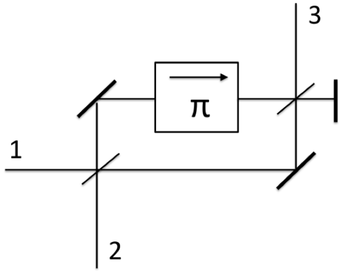
Using gyrator to make a circulator:



$-i\sigma^{-1}Y_{11}$ (blue) $\sigma^{-1}Y_{21}$ (red)



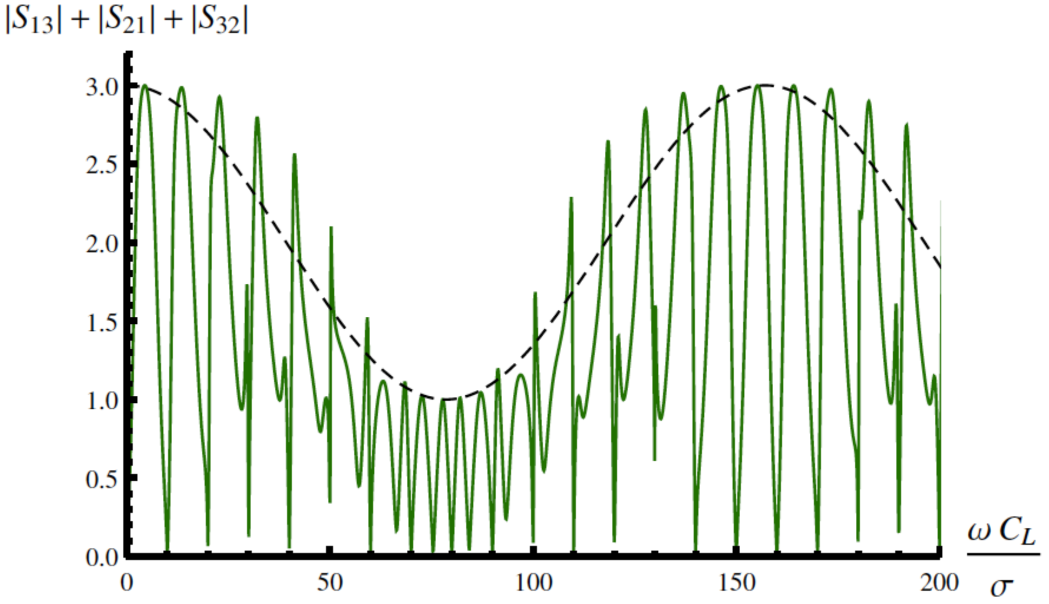
Dispersion comes from c. 10% rounding of c(s) function

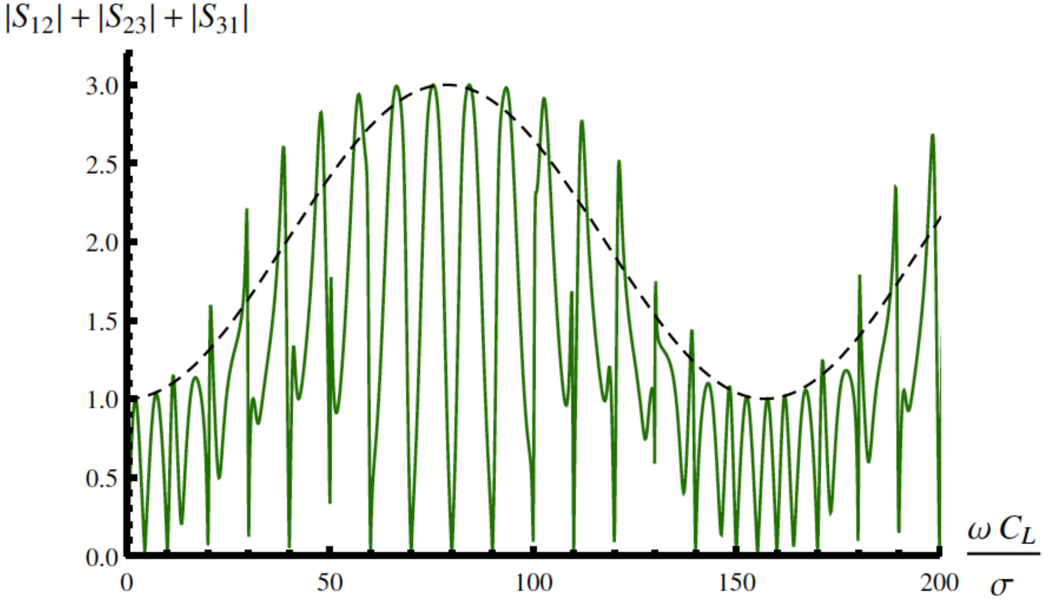


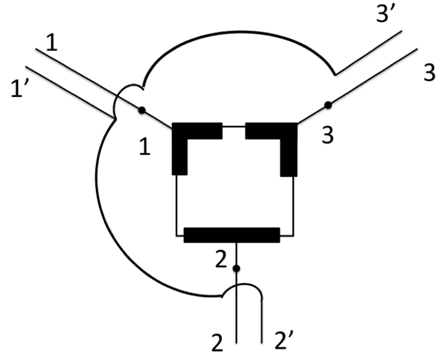
$2^{-1}|S_{12} - S_{21}|$ (green) -- can only be =1 for perfect gyration

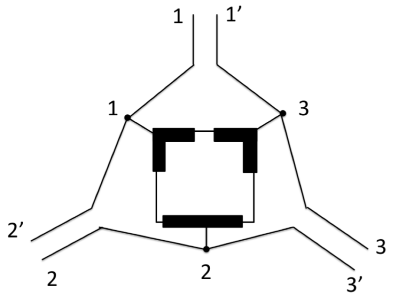
Good gyration over wide frequency bands!

Three-terminal Hall device gives directly a circulator









Carlin (1955)

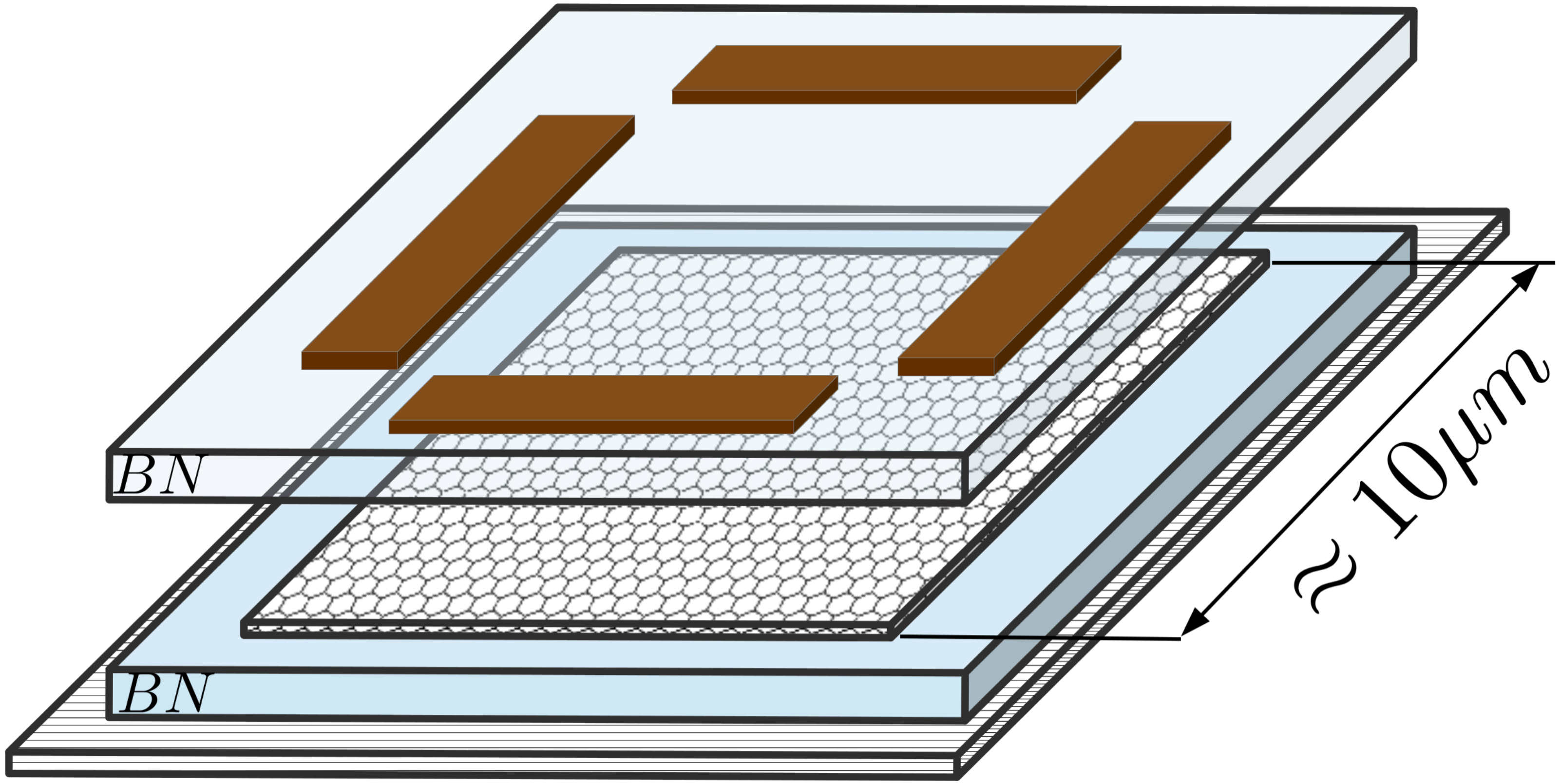
$$Y_{3T,\lambda} = \begin{pmatrix} ia_\lambda & b_\lambda & -b_\lambda^* \\ -b_\lambda^* & ia_\lambda & b_\lambda \\ b_\lambda & -b_\lambda^* & ia_\lambda \end{pmatrix},$$

$$a_\lambda = 2\sigma \frac{\sin\left(\frac{c\omega(\lambda+L)}{\sigma}\right) - \sin\left(\frac{c\lambda\omega}{\sigma}\right)}{1 + 2\cos\left(\frac{c\omega(2\lambda+L)}{\sigma}\right)},$$

$$b_\lambda = \sigma \frac{\exp\left(\frac{-ic\lambda\omega}{\sigma}\right)\left(-1 + \exp\left(\frac{-icL\omega}{\sigma}\right)\right)}{1 + 2\cos\left(\frac{c\omega(2\lambda+L)}{\sigma}\right)}.$$

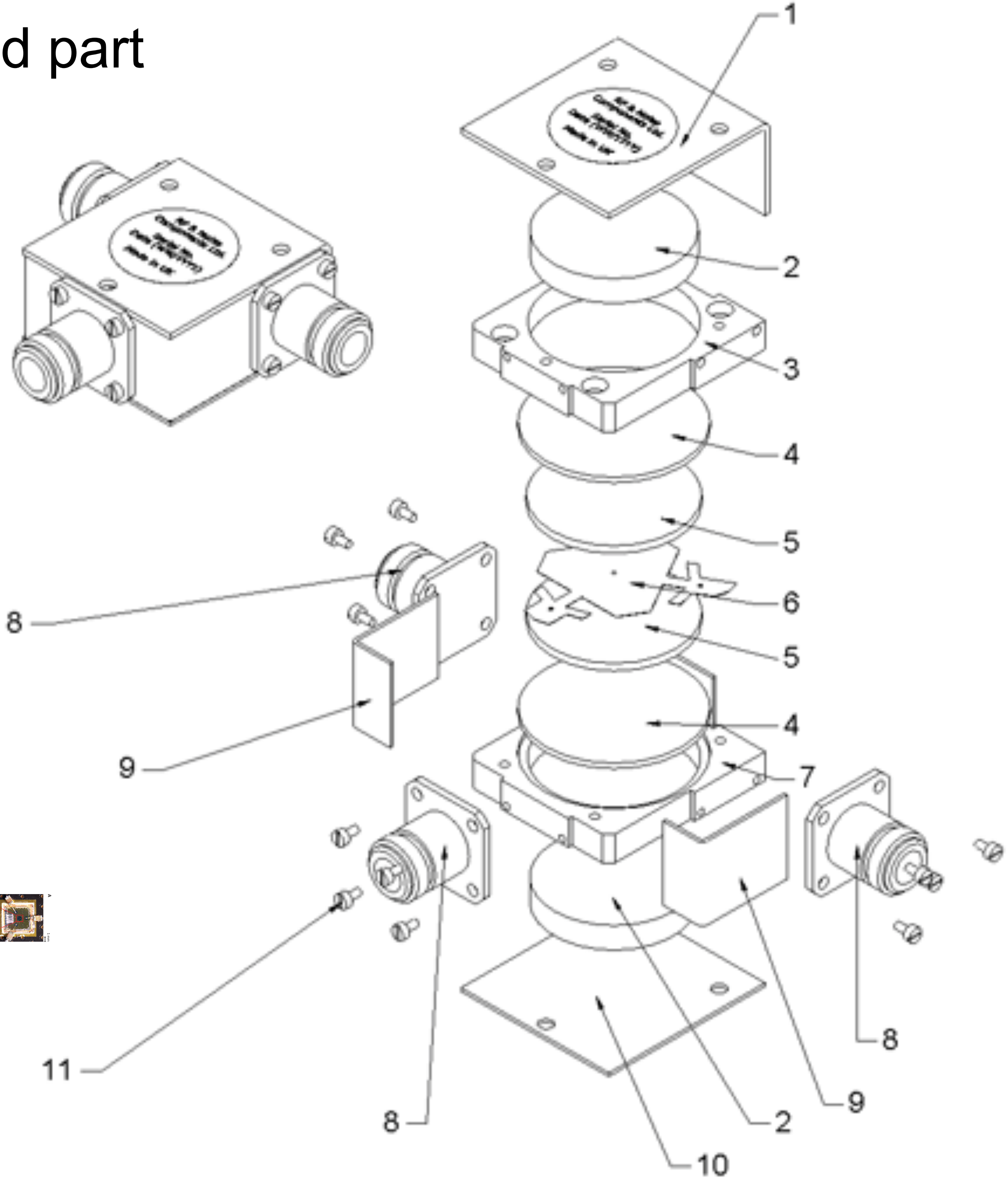
Graphene sandwich of Kim group (2013)

- Capacitive rather than galvanic contact (should be easier)
- A bit small, will gyrate at c. 10 GHz
- Body capacitance easily avoided

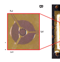


Microwave Circulator:
A complex, engineered part

Basically unchanged
Since c. 1960.

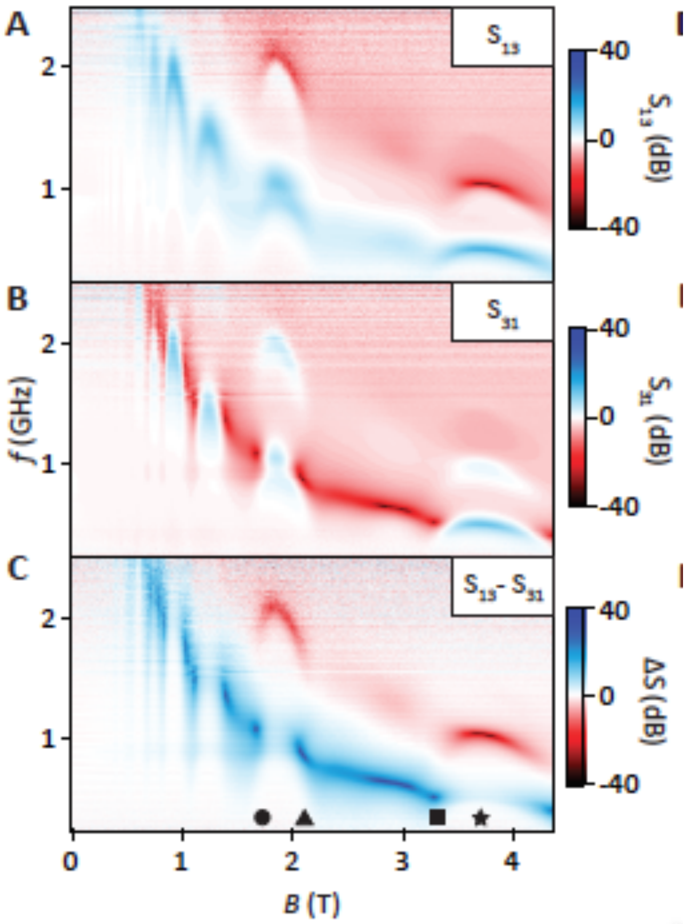


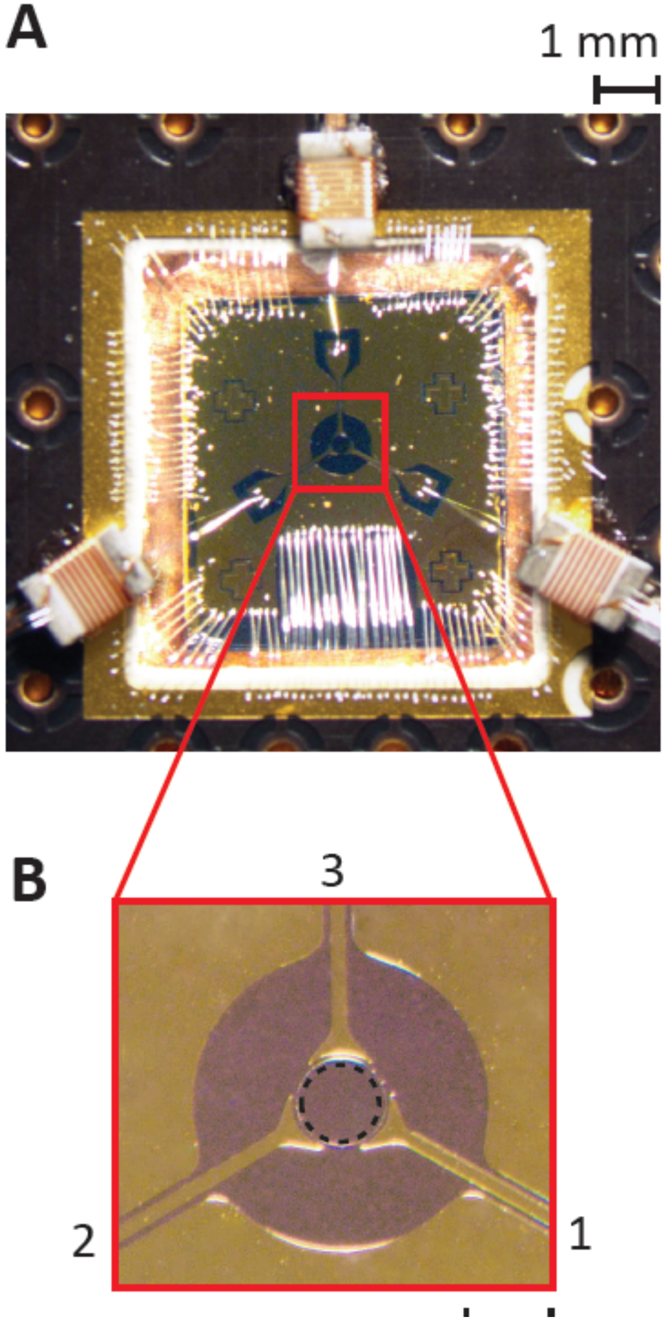
A. Mahoney et al (D. Reilly group), “On-chip quantum Hall microwave circulator”, arXiv: 1601.00634



Miniaturized Microwave Circulator:

A. Mahoney et al (D. Reilly group), “On-chip quantum Hall microwave circulator”, Phys. Rev. X (2017)

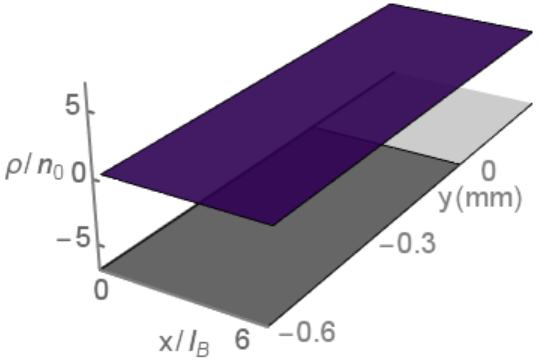




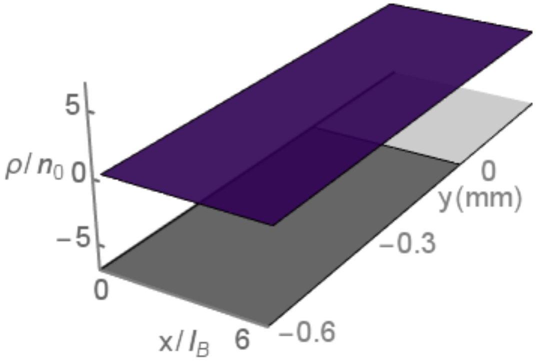
Microscopic plasmon theory

- Edge dynamics of capacitively driven device: chiral edge magnetoplasmon
- Our calculation (RPA with driven electrode (grey))

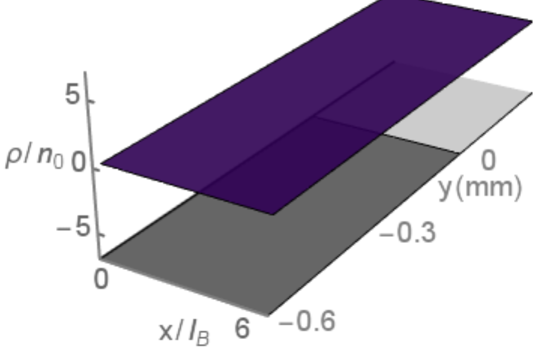
S. Bosco and D. P. DiVincenzo, “Non-reciprocal quantum Hall devices with driven edge magnetoplasmons in 2-dimensional electron gas and graphene,” Phys. Rev. B (accepted)



Fundamental plasmon (fastest)
Monopole charge



Second plasmon
Dipole charge – weak coupling to circuit



Third plasmon
Quadrupole charge – very weak coupling to circuit

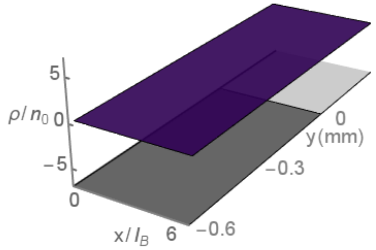
- Relation to Viola-DiVincenzo model:
  - Linear-dispersion plasmons in both
  - VD takes magnetic length to zero
  - VD is one mode, approximating response due to fast plasmon
  - Fast plasmon has dominant coupling due to dipole charge

Overall result: Viola-DiVincenzo is good approximation to microscopic response

Microscopic theory vs. circuit model

$$\frac{\partial u_j(y,t)}{\partial t} + \eta u_j(y,t) = v_j \frac{\partial u_j(y,t)}{\partial y} + a_j \frac{\partial V_e(y,t)}{\partial y}$$

$$a_j \equiv -\frac{e n_0}{m\omega_c} M_{0j}$$



$$\hat{\mu} = \hat{M}\hat{v}\hat{M}^T$$

$$\rho_1(x,y,t) = \sum_j g_j(x) u_j(y,t),$$

$$g_j(x) \equiv \sum_i M_{ij} R_i(x).$$

$$\mu_{ij} \equiv \gamma_{ij} \frac{2n_0 e^2}{\pi^3 m\omega_c \epsilon_S} \int_0^1 ds \frac{T_{2i}(s)}{\sqrt{1-s^2}} \int_0^1 ds' \frac{T_{2j}(s')}{\sqrt{1-s'^2}} \log\left(1 + \left(\frac{2d}{w}\frac{s^2 s'^2}{s^2 - s'^2}\right)^2\right),$$

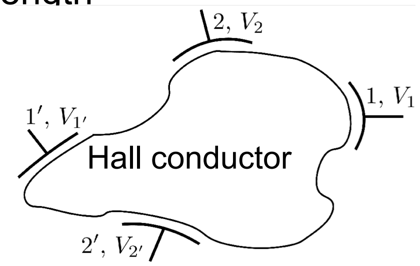
$$R_j(x) \equiv \frac{\sqrt{2}\Theta(x)}{\pi\sqrt{x/w}(x+w)} T_{2j}\left(\frac{1}{\sqrt{1+x/w}}\right)$$

Aleiner & Glazman PRL (1994)
BD (2017)

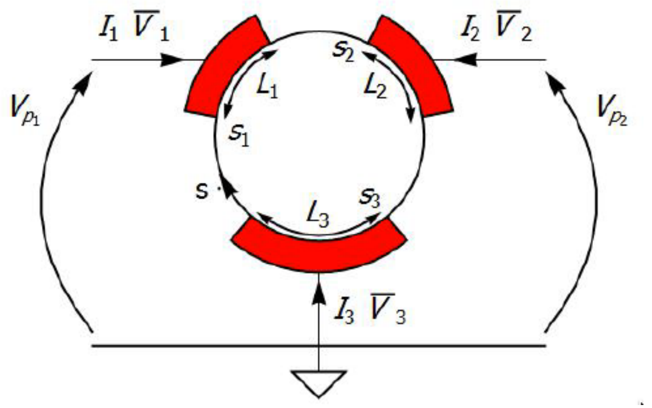
$$\frac{\partial \rho(y,t)}{\partial t} = \frac{\sigma_{xy}}{c}\frac{\partial \rho(y,t)}{\partial y} - \sigma_{xy}\frac{\partial V_e(y,t)}{\partial y}$$

Viola & DiVincenzo, PRX (2014)

- Single component chiral wave equation
- All details of edge dynamics captured by single parameter c: capacitance per unit length



Suggestion for practical device – 50Ω circulator



Gyrator (G)
L_3=2 L_1
L_1= L_2

S. Bosco, F. Haupt, and D. P. DiVincenzo, “Self impedance matched Hall-effect gyrators and circulators,” arXiv:1609.06543

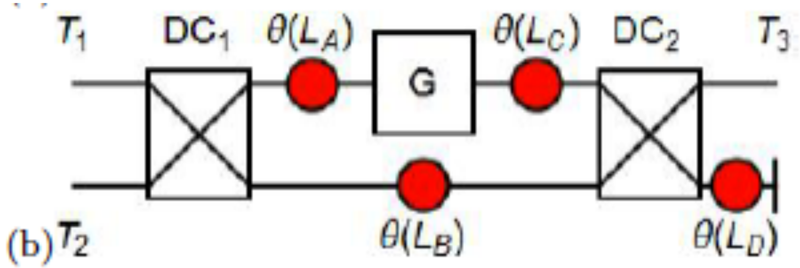


FIG. 8. Circulator construction in optical (a), and microwave (b) conventions. A standard Mach-Zender interferometer is modified by incorporating a gyrator (G) in one of the arms

$$Q_{\circlearrowleft} \equiv |S_{12}| + |S_{23}| + |S_{31}| \leq 3,$$
$$Q_{\circlearrowright} \equiv |S_{21}| + |S_{32}| + |S_{13}| \leq 3,$$

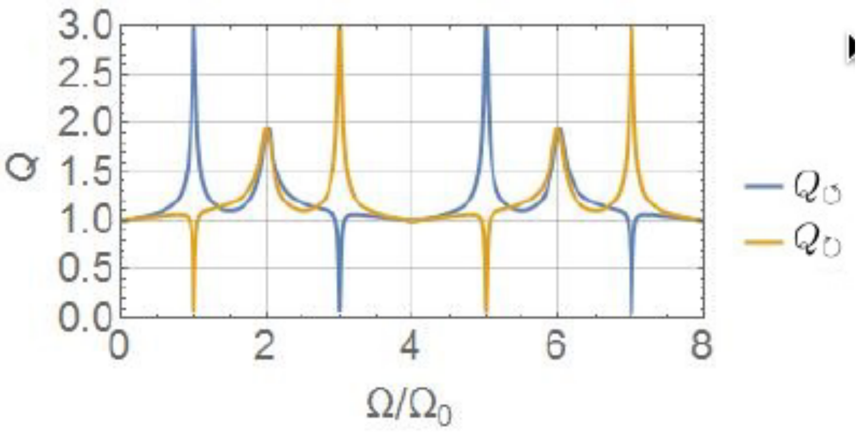


FIG. 10. $Q_{\circlearrowleft}$ and $Q_{\circlearrowright}$ as a function of Ω/Ω_0 in most compact scenario possible, with $L_A = L_B = L_C = L_D = 0$. We used

The Hall Effect Circulator

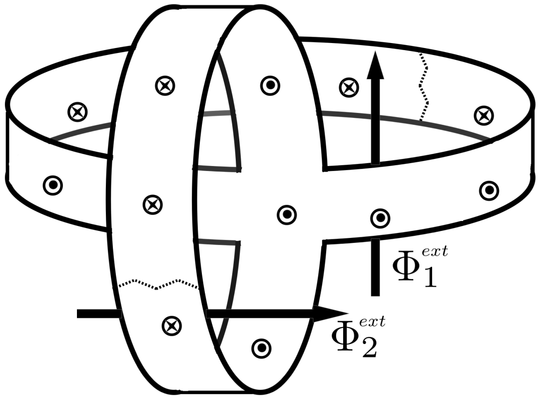
Outline

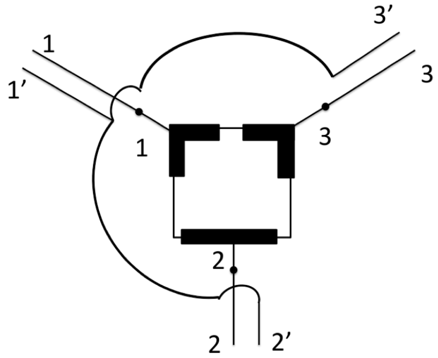
- Role of circulators in qubit experiments
- What is a circulator, and what is a gyrator?
- Faraday effect (bulky) vs. Hall effect – some history
- Our work – capacitive vs. ohmic/galvanic contact
- Dynamics of chiral edge magnetoplasmons
- Experimental situation: new ideas for impedance matching
- New: connection with microscopic theory

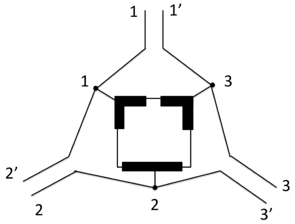
G. Viola and D. P. DiVincenzo, *Hall Effect Gyrators and Circulators,* Phys. Rev. X **4**, 021019 (2014).
S. Bosco, F. Haupt, and D. P. DiVincenzo, *Self impedance matched Hall-effect gyrators and circulators,* arXiv:16

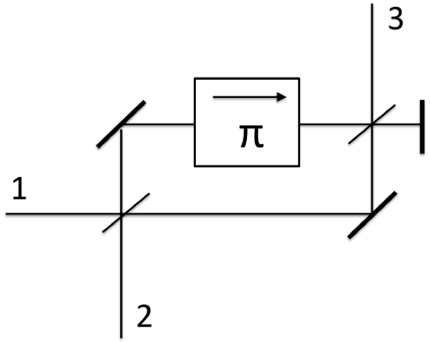
Fin

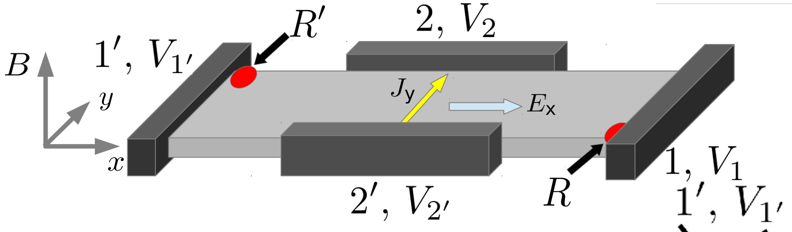
A challenge of scaling up:
classical instrumentation is very complex!

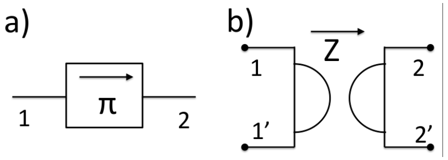


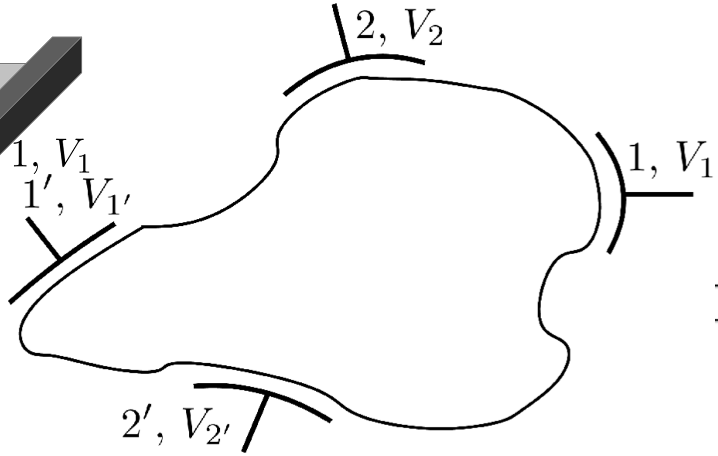


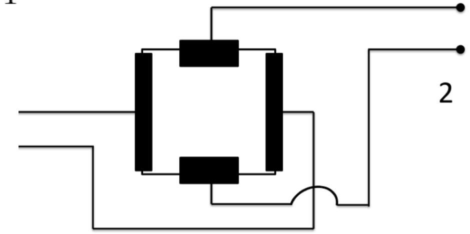






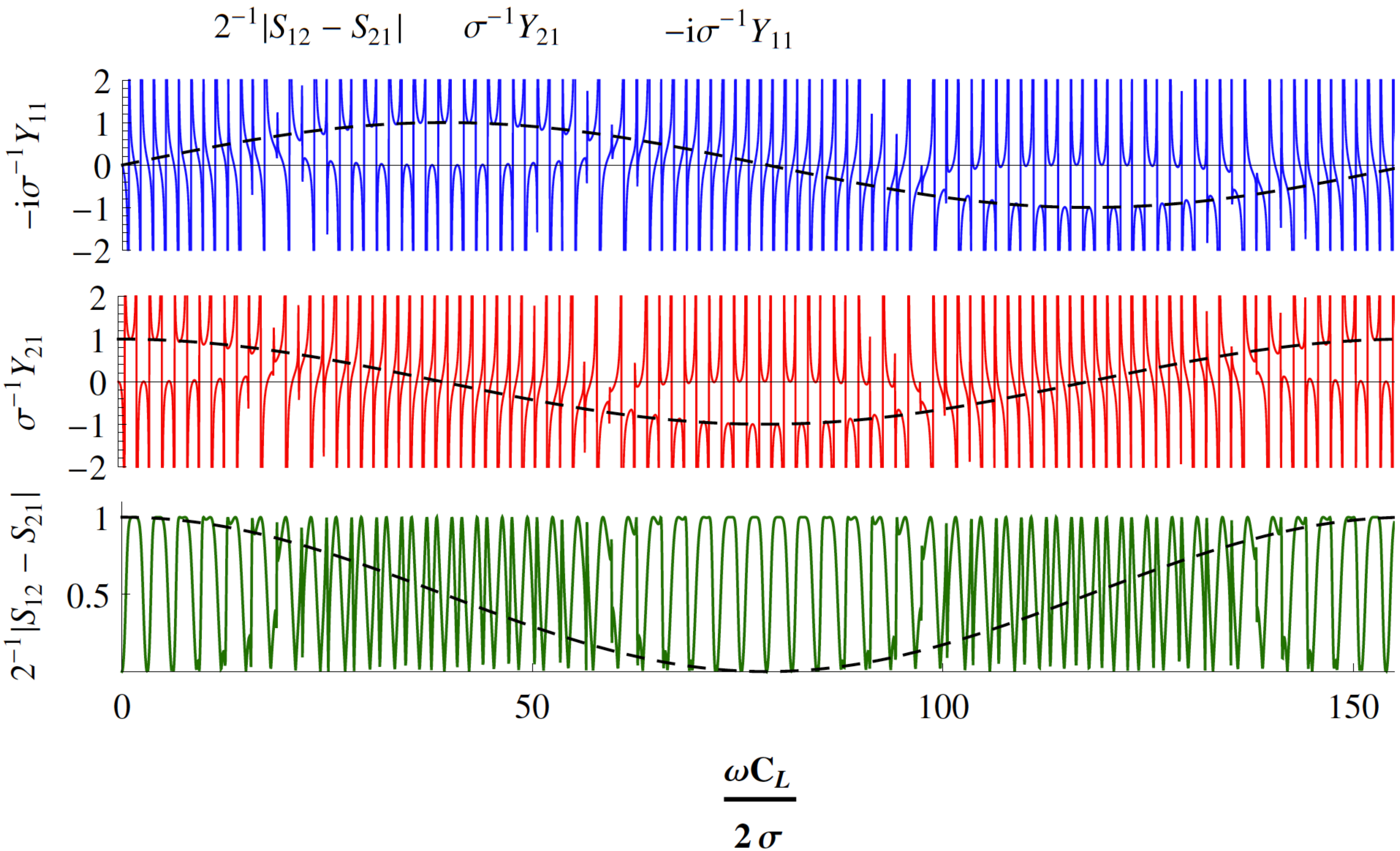






4 per qubit?

A challenge of scaling up: classical instrumentation is very complex!



A challenge of scaling up: classical instrumentation is very complex!

$$S = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\hat{n}_H \cdot \nabla V = 0,$$

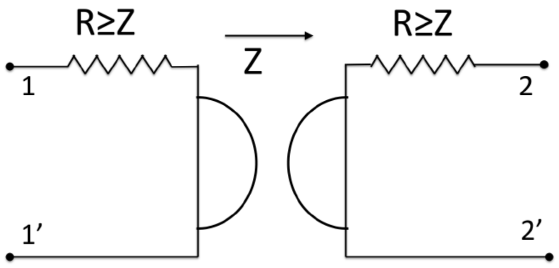
$$\cos\theta_H \frac{\partial V}{\partial n} + \sin\theta_H \frac{\partial V}{\partial s} = 0.$$

$$S = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$\hat{n}_H \cdot \nabla V = 0,$$

$$Z = Z_0 (I + S)(I - S)^{-1}$$

$$\frac{\partial V}{\partial s} = 0.$$



$$\begin{pmatrix} j_x \\ j_y \end{pmatrix} = \sigma \begin{pmatrix} \cos\theta_H & \sin\theta_H \\ -\sin\theta_H & \cos\theta_H \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}, \quad \sigma \equiv \frac{\cos\theta_H}{\rho}$$

$$\nabla^2 V(x, y) = 0$$

$$P_{diss.} = \int_A \vec{E} \cdot \vec{j}\, dx dy = \cos\theta_H \int_A |\vec{E}| \cdot |\vec{j}|\, dx dy.$$

4 per qubit?

$$-\vec{\nabla} V = \vec{E} = \rho \vec{j} - R_H \vec{j} \times \vec{H}.$$

A challenge of scaling up: classical instrumentation is very complex!

$$\omega_n = \frac{2n\pi\sigma}{\int_0^P c(s)ds}.$$

$$Y_{2P}(\omega) = \frac{\sigma}{2}\begin{pmatrix} i\tan\frac{\omega C_L}{\sigma} & -1+\sec\frac{\omega C_L}{\sigma} \\ 1-\sec\frac{\omega C_L}{\sigma} & i\tan\frac{\omega C_L}{\sigma} \end{pmatrix},$$

ch when inverted gives the two-port impedance

$$\nabla^2 V(x,y) = 0.$$

$$Z_{2P}(\omega) = \frac{1}{\sigma}\begin{pmatrix} -i\cot\frac{\omega C_L}{2\sigma} & -1 \\ 1 & -i\cot\frac{\omega C_L}{2\sigma} \end{pmatrix}.$$

$$\sigma\,\hat{n}_H \cdot \nabla V(s,\omega) = i\omega c(s)(\bar{V}(\omega) - V(s,\omega)).$$

$$-\vec{\nabla}V = \vec{E} = \rho\vec{j} - R_H\vec{j}\times\vec{H}.$$

$$\hat{n}\cdot\vec{j}(s,t) = j_D(s,t) = c(s)\frac{d}{dt}(V(t) - V(s,t)).$$

$$Y_{3T,\lambda} = \begin{pmatrix} ia_\lambda & b_\lambda & -b_\lambda^* \\ -b_\lambda^* & ia_\lambda & b_\lambda \\ b_\lambda & -b_\lambda^* & ia_\lambda \end{pmatrix},$$

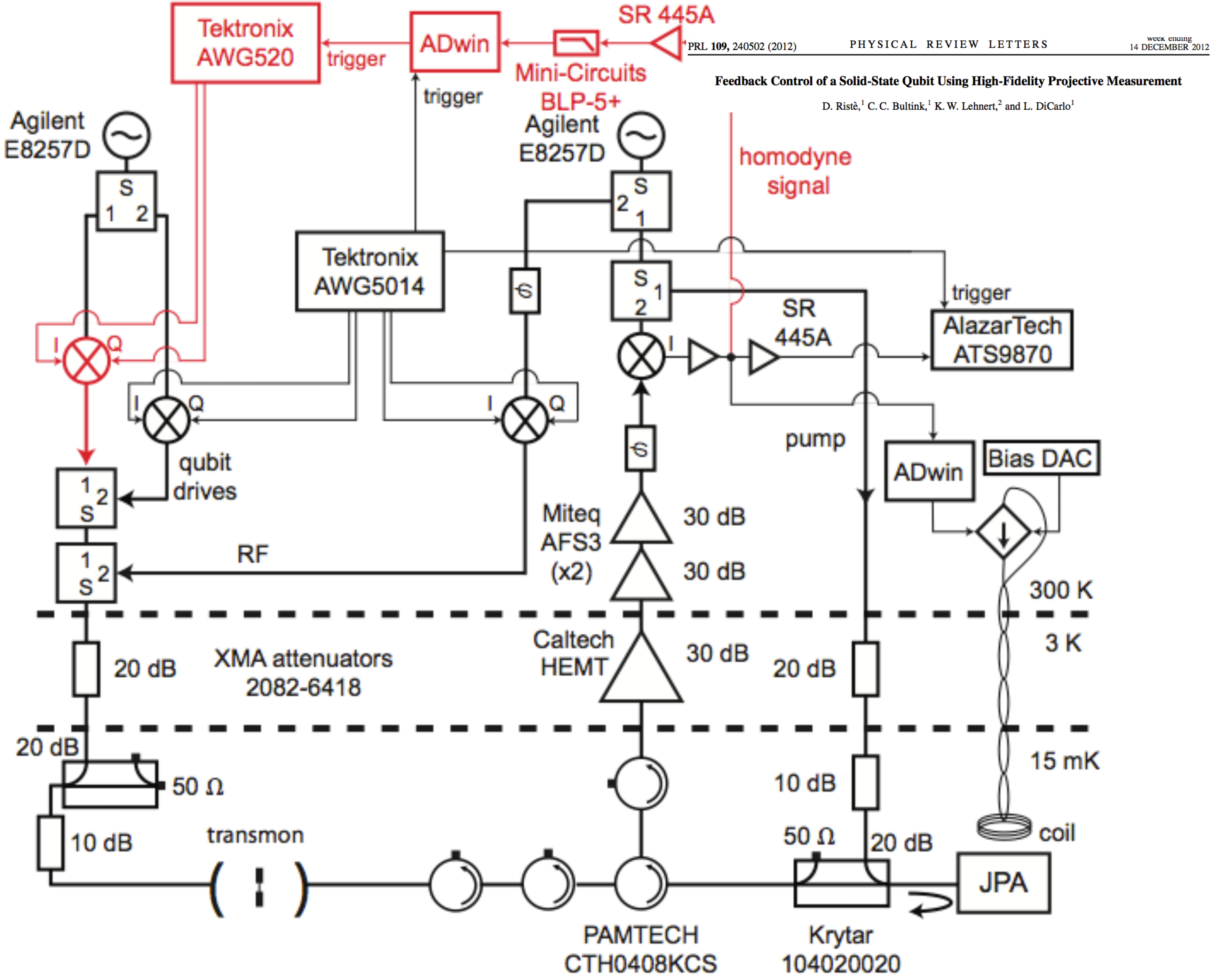
$$-\sigma\frac{\partial V(s,\omega)}{\partial s} = i\omega c(s)(\bar{V}(\omega) - V(s,\omega)).$$

$$a_\lambda = 2\sigma\frac{\sin\left(\frac{c\omega(\lambda+L)}{\sigma}\right) - \sin\left(\frac{c\lambda\omega}{\sigma}\right)}{1+2\cos\left(\frac{c\omega(2\lambda+L)}{\sigma}\right)},$$

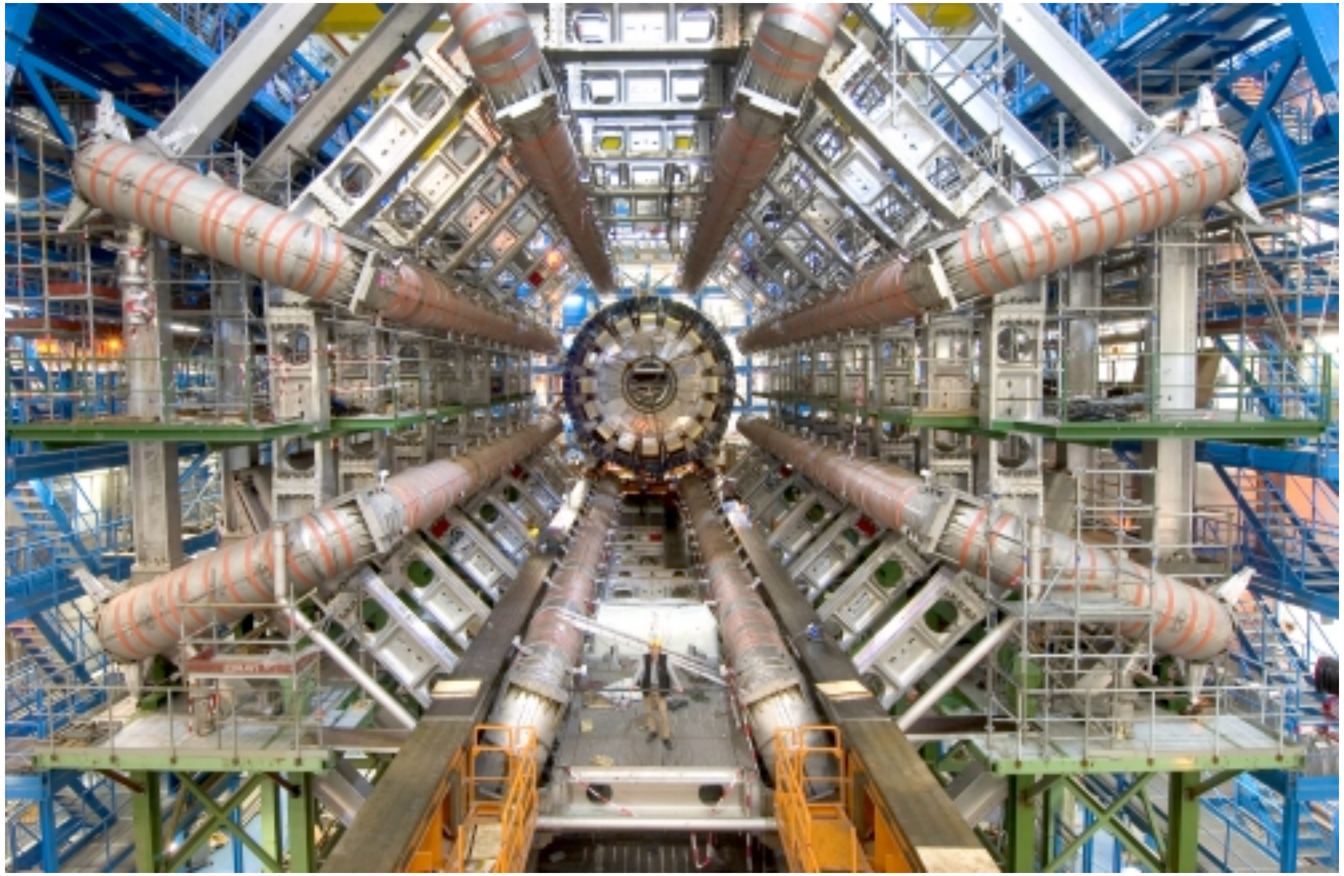
σ

$$b_\lambda = \sigma\frac{\exp(\frac{-ic\lambda\omega}{\sigma})\left(-1+\exp(\frac{-icL\omega}{\sigma})\right)}{1+2\cos\left(\frac{c\omega(2\lambda+L)}{\sigma}\right)}.$$

A History of
the Circulator


PRL 109, 240502 (2012)
PHYSICAL REVIEW LETTERS
week ending 14 DECEMBER 2012
Feedback Control of a Solid-State Qubit Using High-Fidelity Projective Measurement
D. Ristè,[1] C. C. Bultink,[1] K. W. Lehnert,[2] and L. DiCarlo[1]
SR 445A
Tektronix AWG520
trigger
ADwin
Mini-Circuits BLP-5+
trigger
Agilent E8257D
Agilent E8257D
homodyne signal
S 1 2
Tektronix AWG5014
S 2 1
S 1 2
trigger
AlazarTech ATS9870
SR 445A
I
Q
I
Q
I
Q
I
qubit drives
pump
ADwin
Bias DAC
1 2 S
1 2 S
RF
Miteq AFS3 (x2)
30 dB
30 dB
300 K
3 K
20 dB
XMA attenuators 2082-6418
Caltech HEMT
30 dB
20 dB
15 mK
20 dB
50 Ω
10 dB
10 dB
transmon
50 Ω
20 dB
coil
JPA
PAMTECH CTH0408KCS
Krytar 104020020

ATLAS detector, CERN – classical instrumentation is most of the picture,
Much larger than quantum parts



(19) Canadian Intellectual Property Office | Office de la Propriété Intellectuelle du Canada

(11) **CA 511631** (13) **A**

(40) **05.04.1955**

(71) Applicant: **PHILIPS NV.**

(72) Inventor: **TELLEGEN BERNARDUS D H ().**

(54) **GYRATOR**

(57) **Abstract:**

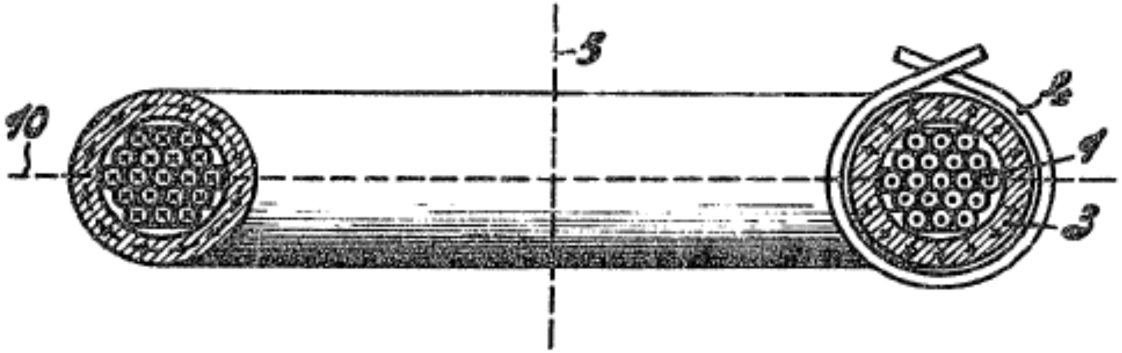


Fig.1

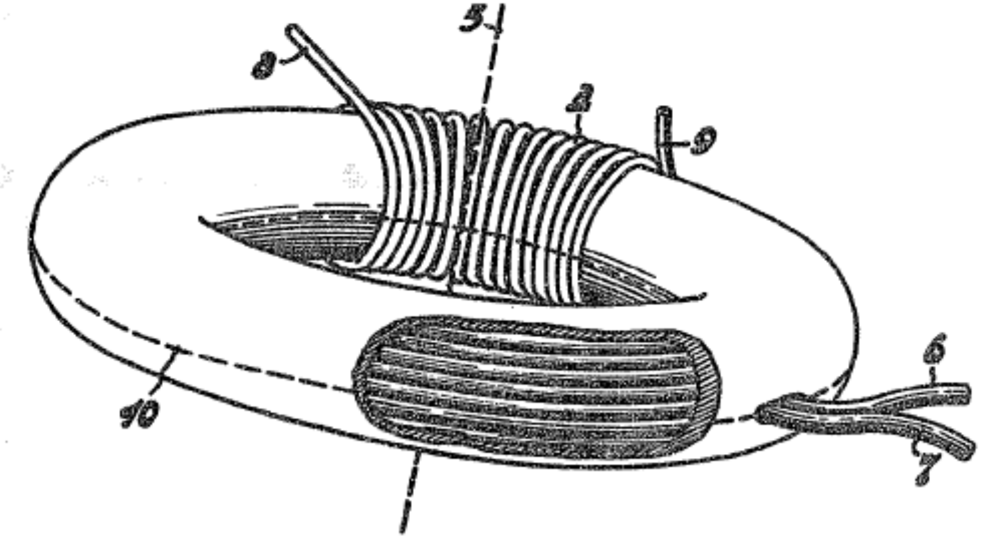


Fig.2.

Prospects for Superconducting Qubits, & The History of the Circulator

Outline

- Short history of quantum effects in superconducting devices
- A Moore's law for quantum coherence
- Scaling up with cavities – towards a surface code architecture
- Will it work??
- Lots of engineering/physics will be needed!
- Case study – the electrical circulator
- Innovations are possible, and are definitely needed

*"In a machine such as this there are very many other problems due to imperfections. . . .
At least some of these problems can be remedied in the usual way by techniques
such as error correcting codes . . . But until we find a specific implementation
for this computer, I do not know how to proceed to analyze these effects."*

R.P. Feynman
"Quantum Mechanical Computers"
Optics News, February 1985