Lecture 7

of

EEE307

Electronics for Communications

Department of Electrical & Electronic Engineering

Xi'an Jiaotong-Liverpool University (XJTLU)

Friday, 1st November 2019

- Mixer in transceivers
- Mixer mathematics
  - frequency translation by switching action
- MOSFET & diode implementations
  - single-balanced & double-balanced
  - diode as a switch

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Wireless Communication Systems

(frequency translation)

- In wireless communication systems, there is a common need to ***translate*** **signals** from one **frequency** to another.
  - The **carrier frequency** at which data is transmitted using **electromagnetic** (**EM**) **waves** propagating in air (or in space) can be from about 30 MHz to 300 GHz.
  - The frequency of the baseband signals is typically below 10 MHz: bandwidth for analogue voice signals ≈ 3.1 kHz; ≈ 6 MHz (4.2 MHz if video only) for TV signals.

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Wireless Communication Systems

(frequency translation)

- To ***translate*** **radio frequency (RF) signals** from the **carrier frequency** to lower frequencies (e.g. baseband or intermediate frequency) and vice versa, a **mixer** is needed.

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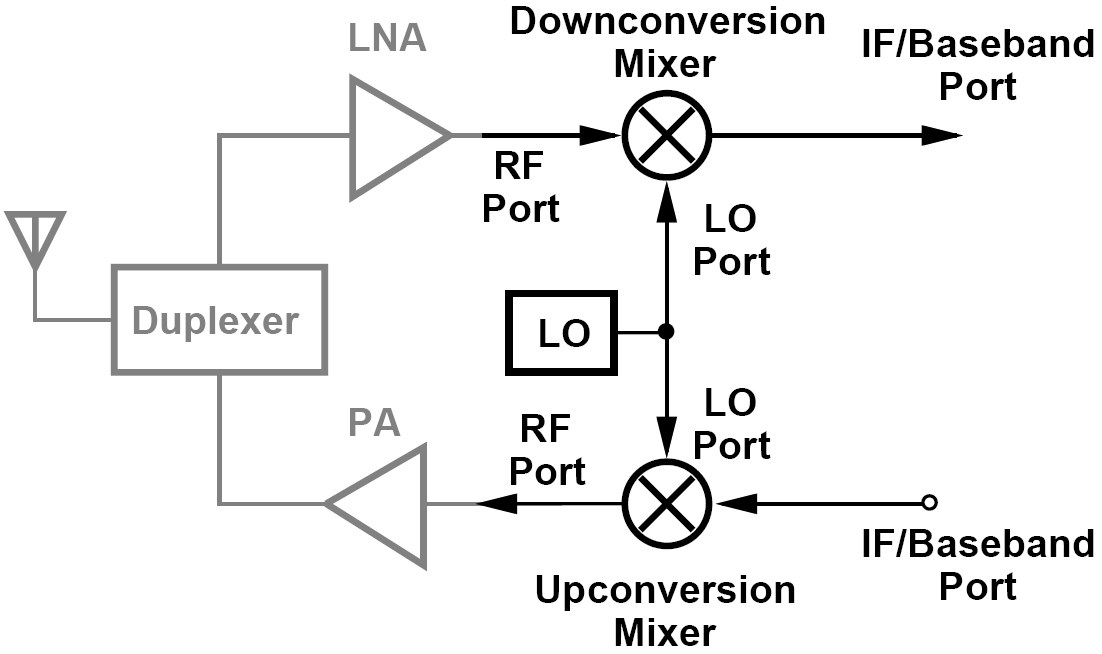

- A mixer appears in the receive path and the transmit path, respectively called **downconversion mixer** and **upconversion mixer**.

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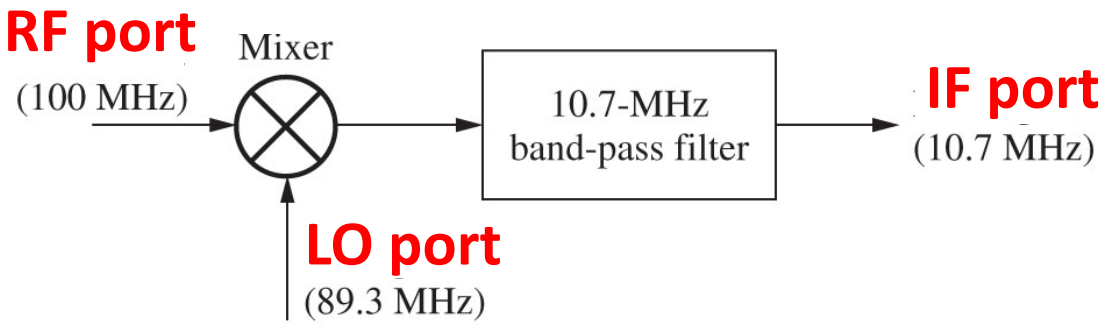
RF Mixer

(frequency translation)

- A **mixer** perform **frequency translation** by ***multiplying*** two waveforms (and perhaps their harmonics too).
  - For this reason, a mixer has three distinctly different ports.
  - In a wireless transmitter or receiver, the three ports of a mixer are typically called the **RF port**, **LO port** and **IF port**, where **LO**: local oscillator, **IF**: intermediate frequency.



Adapted from: R. C. Jaeger & T. N. Blalock, *Microelectronic Circuit Design*, 4e, © 2010 McGraw-Hill, USA.

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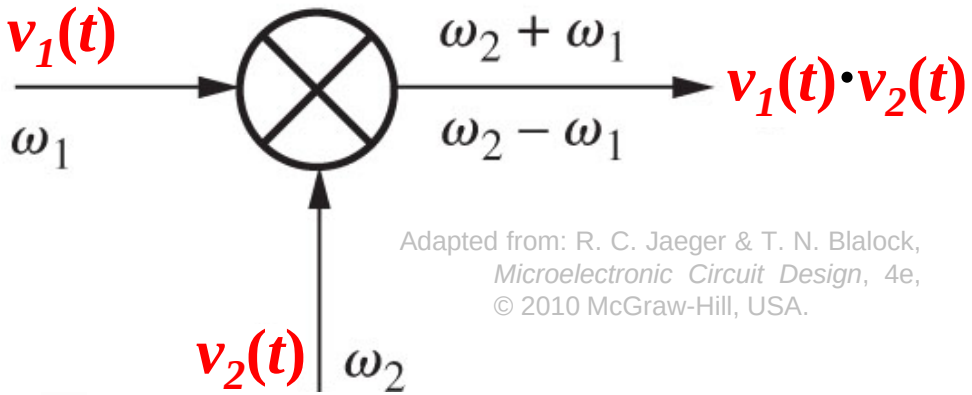
RF Mixer – frequency translation

(multiplication of two waveforms)

- The **frequency translation** performed by the **multiplication** of two waveforms in a **mixer** is obvious by looking at the product of two sinusoidal waveforms.
  - Using standard trigometric identities,

$$v_1(t)\cdot v_2(t) = A_1\sin(\omega_1 t)\cdot A_2\sin(\omega_2 t) = A_1A_2\,\frac{\cos[(\omega_2-\omega_1)t]-\cos[(\omega_2+\omega_1)t]}{2}$$



- The ideal mixer output contains signal components at frequencies $(\omega_2-\omega_1)$ & $(\omega_2+\omega_1)$.

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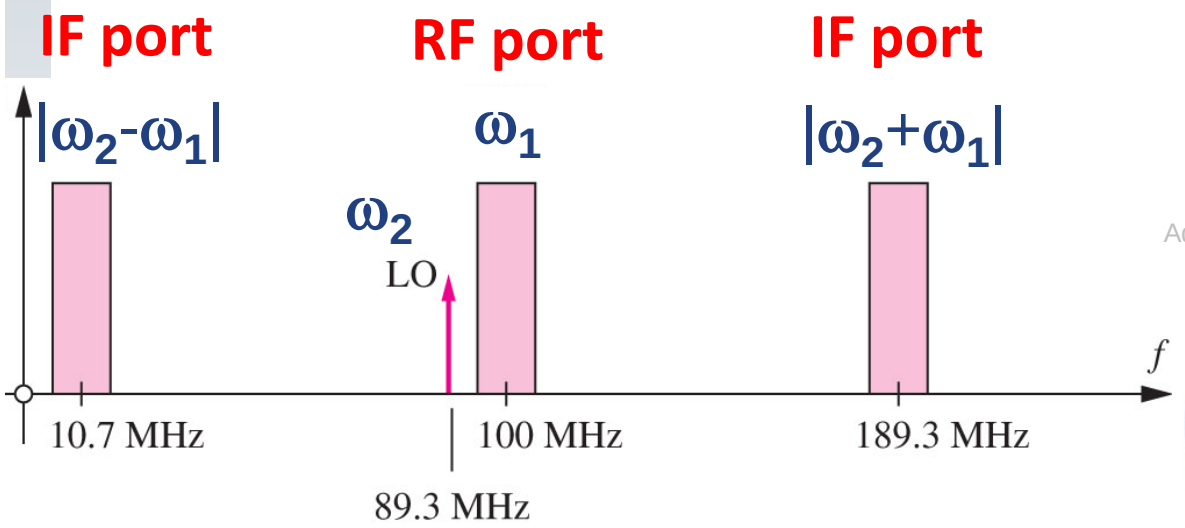
RF Mixer – frequency translation

(downconversion & upconversion)

- In a **downconversion mixer** in the receive path, the signal component of the frequency difference **(ω_2-ω_1)** is selected using a filter.
- In an **upconversion mixer**, the signal component of the frequency sum **(ω_2+ω_1)** is selected.



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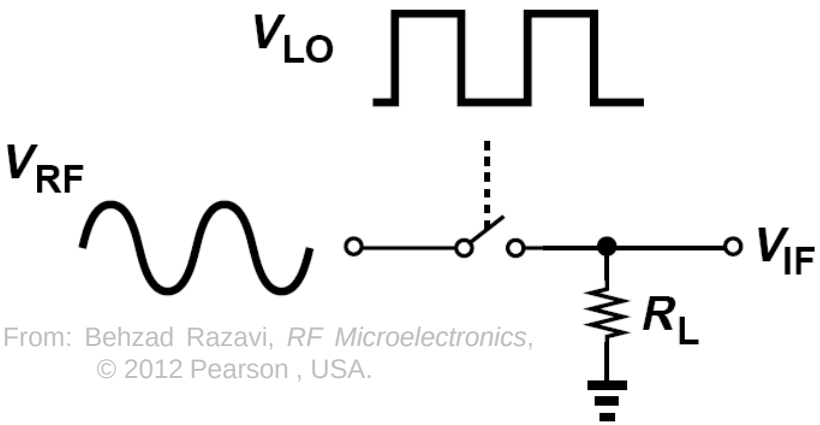
RF Mixer – signal multiplication

(switch as a non-linear device)

- In general, any ***non-linear*** **device** can be used for ***multiplying*** of two waveforms and hence can work as a **mixer**.
- A **switch** is such a **non-linear device** for *multiplying* two signals to achieve the **frequency translation**.



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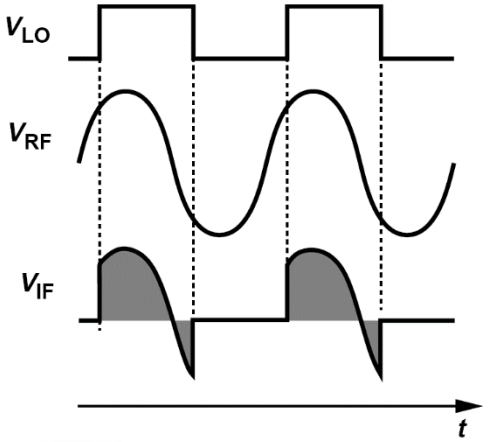
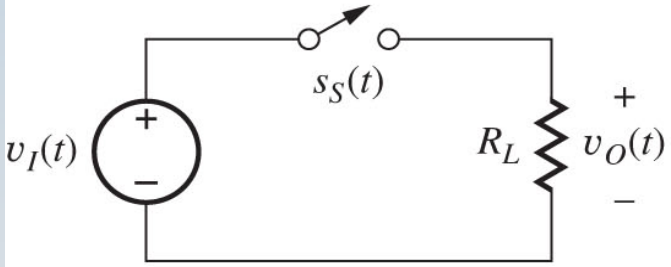


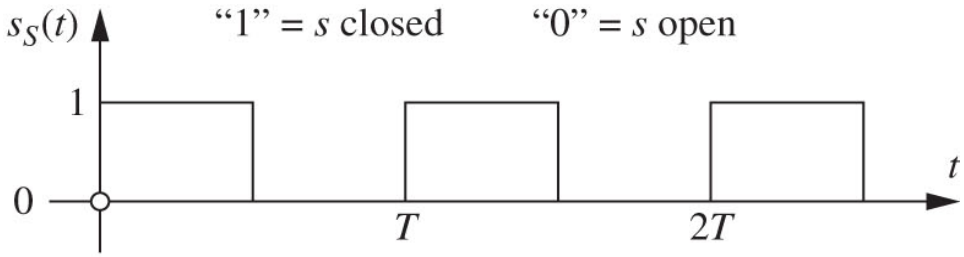
- What is the frequency spectrum like?

RF Mixer – signal multiplication

(mixer mathematics)

- The action of the switch in the time domain is equivalent to a square waveform.





$$v_I(t) = A_1 \sin(\omega_1 t)$$

$$s_S(t) = \frac{1}{2} + \frac{2}{\pi} \sum_{n=1,3\ldots} \frac{1}{n} \sin(n\omega_2 t), \text{ with } \omega_2 = \frac{2\pi}{T}$$

$$v_O(t) = v_1(t) \cdot s_S(t) = \frac{A_1}{2} \sin(\omega_1 t) + \frac{2A_1}{\pi} \sum_{n=1,3\ldots} \frac{1}{n} \sin(n\omega_2 t) \sin(\omega_1 t)$$

$$v_O(t) = \frac{A_1}{2} \sin(\omega_1 t) + \frac{2A_1}{\pi} \sum_{n=1,3\ldots} \frac{1}{n} \frac{\cos[(n\omega_2 - \omega_1)t] + \cos[(n\omega_2 + \omega_1)t]}{2}$$

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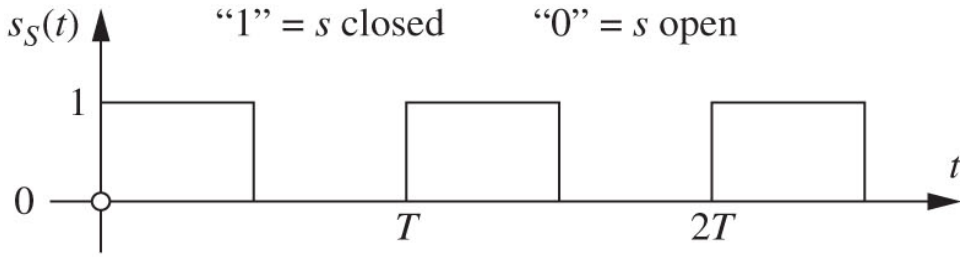
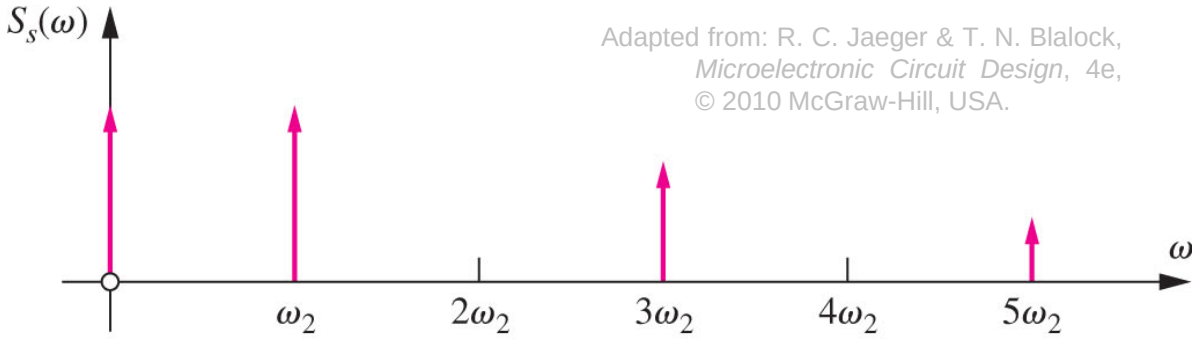
RF Mixer – signal multiplication (spectrum)

- The action of the switch in the time domain is equivalent to a square waveform.



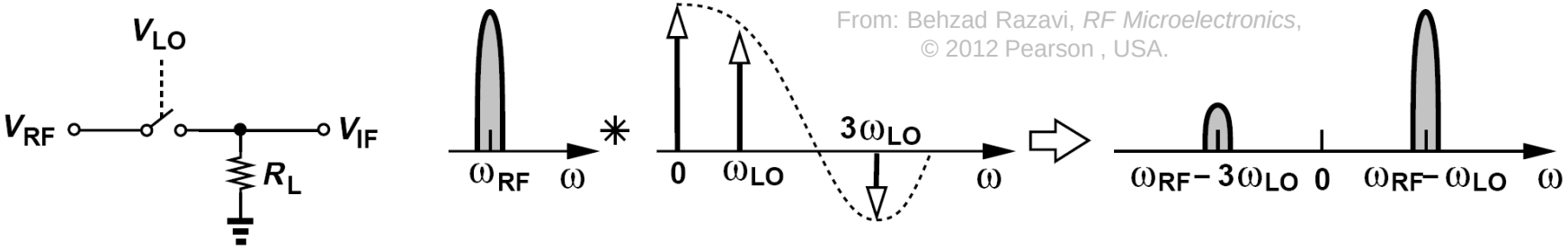
$$s_S(t) = \frac{1}{2} + \frac{2}{\pi} \sum_{n=1,3...} \frac{1}{n} \sin(n\omega_2 t), \text{ with } \omega_2 = \frac{2\pi}{T}$$



RF Mixer – signal multiplication

(spectrum)

- In general, any ***non-linear*** **device** can be used for ***multiplying*** of two waveforms and hence can work as a **mixer**.
- A **switch** is such a **non-linear device** for *multiplying* two signals to achieve the **frequency translation**.



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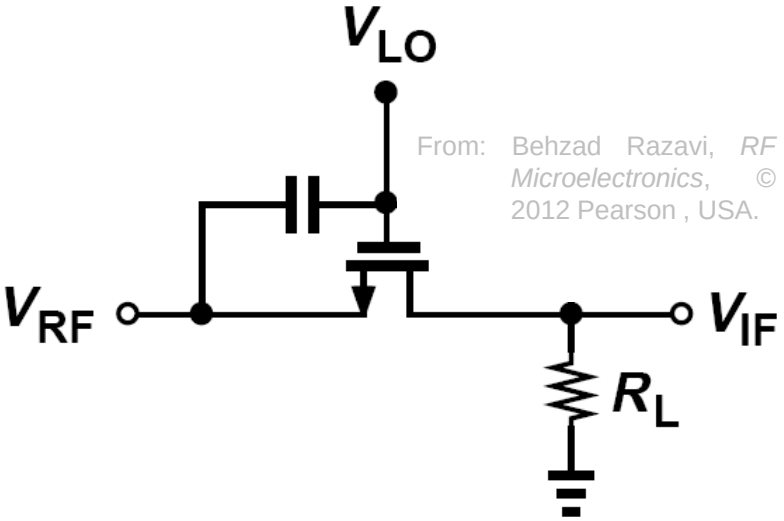
Simple RF Mixer

(using MOS transistor as a switch)

- As a MOS transistor can serve as a switch, it can be used to build a very simple **mixer**.



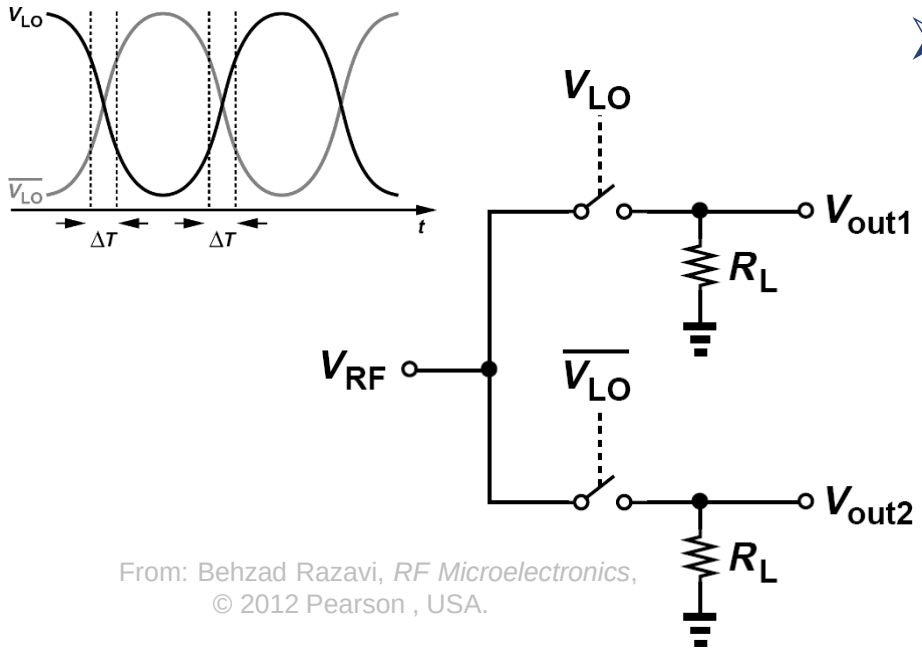
- Such a mixer operates with a single-ended RF input and a single-ended LO signal.
- It is not an efficient approach as the RF signal is discarded for half of the LO period.

$$v_{IF}(t) = v_{RF}(t) \times \frac{2}{\pi} \sum_{n=1,3...} \frac{1}{n} \sin(n\omega_{LO})t = v_{RF}(t) \times \frac{2}{\pi} \sin(n\omega_{LO})t + ...$$

Single-Balanced Passive Mixer

(balanced LO waveforms)

- A more efficient approach to the construction of a **mixer** in using the MOS transistor as a switch is to have a differential LO signal to drive two MOS transistor switches.



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

- The differential LO signal then commutates the RF input to the two outputs.

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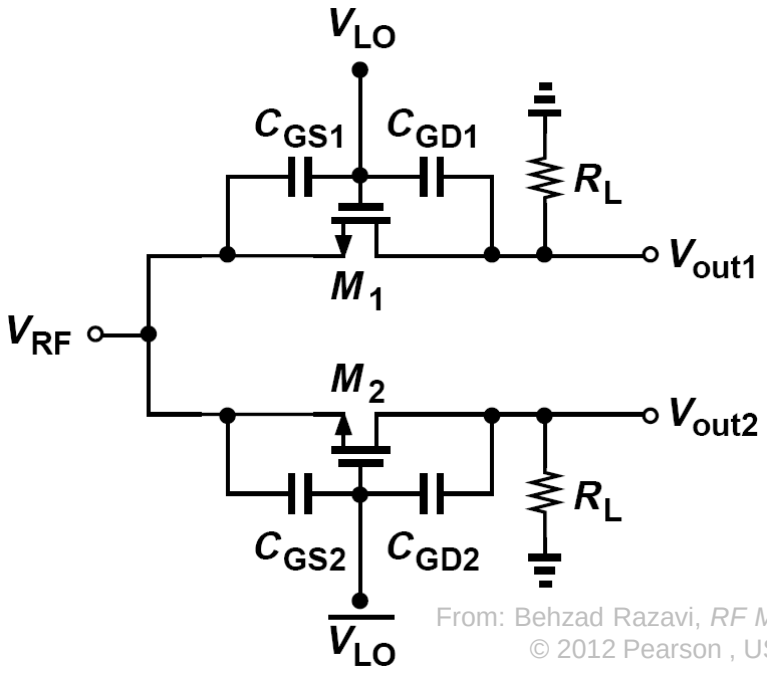
Single-Balanced Passive Mixer

(balanced LO waveforms)

- Such a **passive mixer** is called **single-balanced mixer** because of the ***balanced*** LO waveform in the multiplication with the RF signal.



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- The configuration provides twice the conversion gain of the mixer using only one MOS transistor switch.

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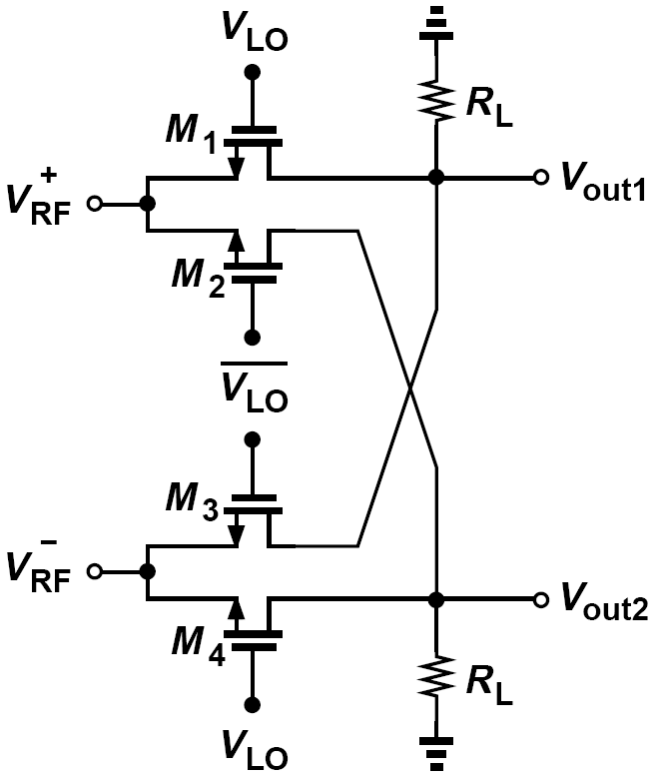
Double-Balanced Passive Mixer

(combining two single-balanced mixers)

- An improved configuration is to have the ***balanced*** RF input in addition to the ***balanced*** LO waveforms.



- This is called a **double-balanced mixer**, formed by connecting two **single-balanced mixers** such that their output LO feedthrough cancel but their output signals do not.

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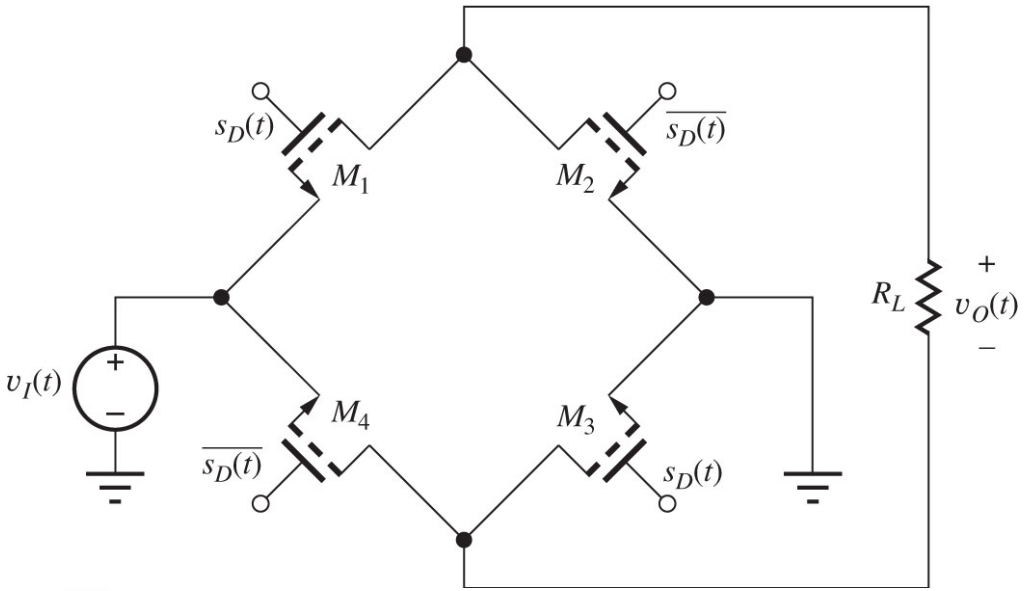
From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

Double-Balanced Passive Mixer

(single-ended RF input)

- The double-balanced mixer can also be configured in a slightly different way.
  - Note that the RF input is single-ended which is not an uncommon output from the LNA.

Adapted from: R. C. Jaeger & T. N. Blalock, *Microelectronic Circuit Design*, 4e, © 2010 McGraw-Hill, USA.



  - With one differential input grounded to accommodate a single-ended RF input, the input-referred noise is higher.

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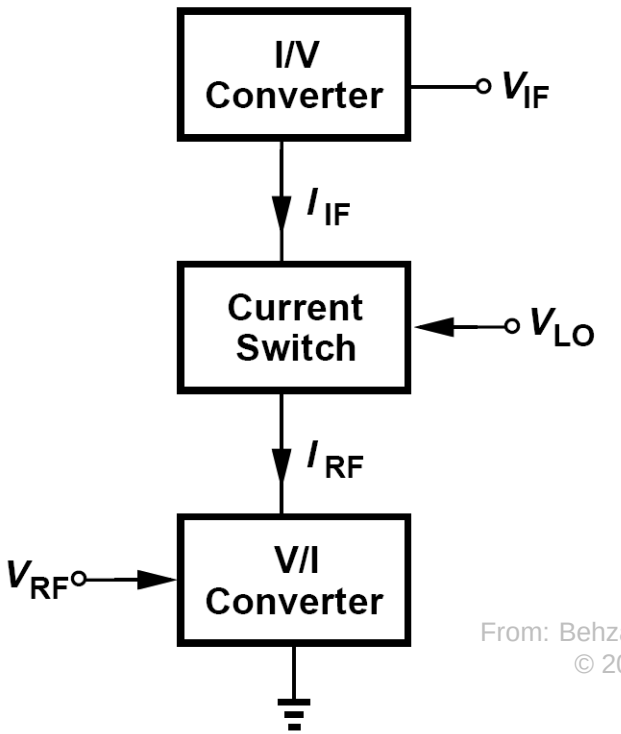
Active Mixer

(I-V & V-I conversion)

- While **passive mixers** using MOS transistors as **switches** provide no conversion gain (except with a large-amplitude LO signal), ***active*** **mixers** can be built by using transistors to



  - convert the RF signal into a current,
  - commutate (steer) the RF current signal by the LO signal,
  - convert the IF current signal to a voltage signal.

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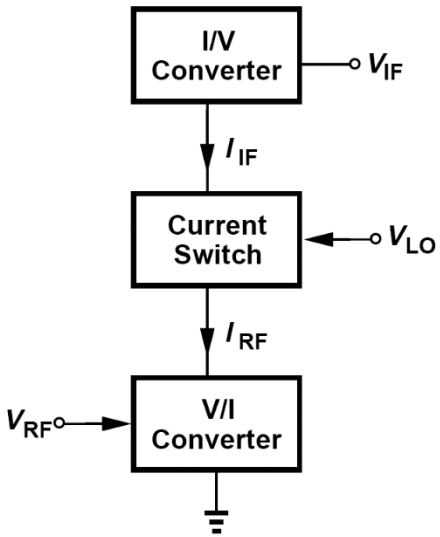
Active Mixer

(switching current signal)

- Such an ***active*** **mixers** incorporates **switching** for **frequency translation** after the voltage-to-current conversion but before the current-to-voltage conversion.



  - In the input *I*-*V* conversion, the input transconductance I_{RF}/V_{RF} can be arbitrarily high.
  - In the output *V*-*I* conversion, the output transresistance V_{IF}/I_{IF} can also be arbitrarily high.
  - A high signal gain can be obtained from such an active mixer in the whole process while the switching provides no gain.

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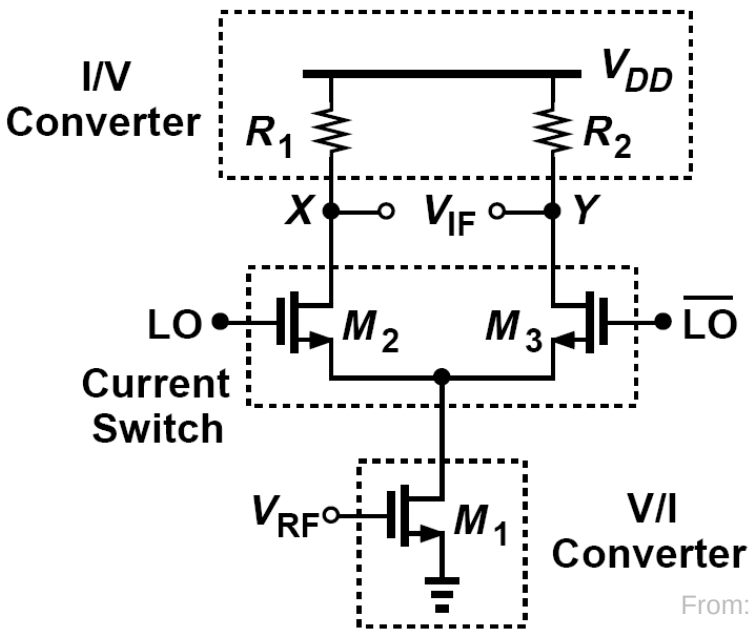
From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

Single-Balanced Active Mixer

(use of 3 transistors & 2 resistors)

- A typical *single-balanced* realisation of such an ***active*** **mixers** uses at least three transistors.
  - Transistor M_1 converts the input RF voltage to a current signal.

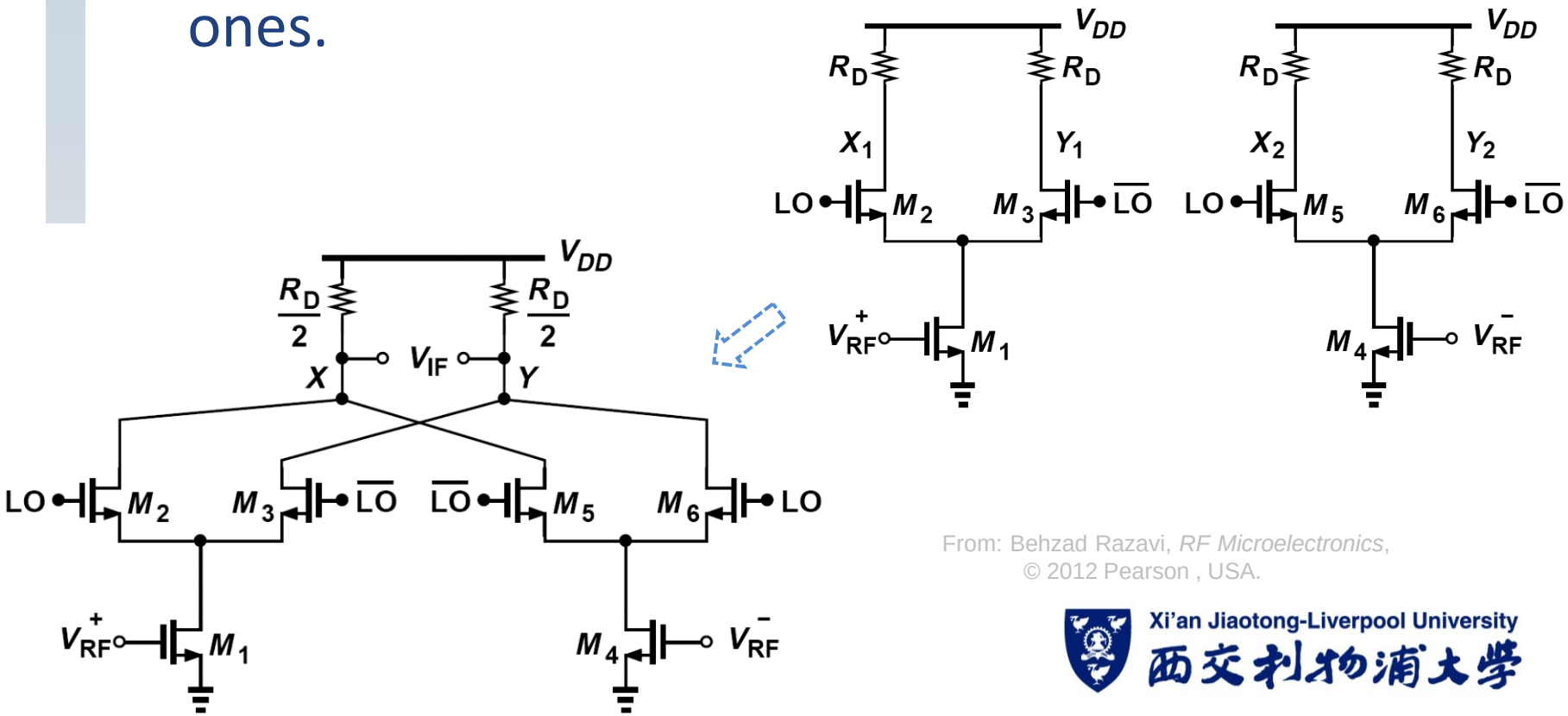


  - The differential transistor pair M_2 and M_3 commutates (steers) the RF current signal to the left and to the right.
  - The resistors $\boldsymbol{R_1}$ and $\boldsymbol{R_2}$ convert the output currents to a voltage signal.

Double-Balanced Active Mixer

(combining two single-balanced mixers)

- A ***double-balanced*** realisation of the active mixer can be obtained by combining two single-balanced ones.



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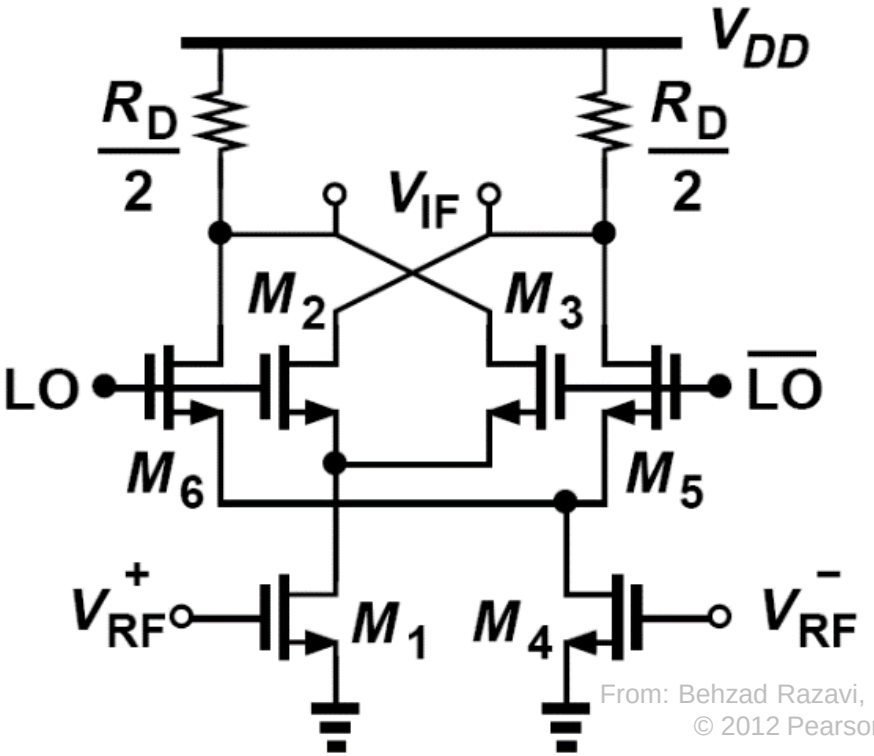
Double-Balanced Active Mixer

(Gilbert cell)

- The transistor configuration in the double-balanced active mixer is commonly referred to the **Gilbert cell** or **Gilbert multiplier**.



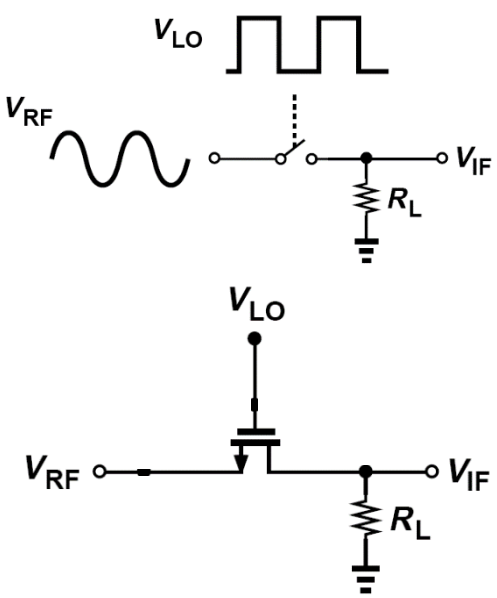
  - It was invented in 1960's by B. Gilbert (and also by H. Jones). Bipolar junction transistors (BJTs) were used in the initial circuit.

From: Behzad Razavi, *RF Microelectronics*,

Switching Action – key in mixers

(switching in voltage or current modes)

- In the operation of mixers to achieve **frequency translation** by the **multiplication** of two electrical signals, the key is the **switching** action.



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

- It can be **switching** in the **voltage mode** or **current mode** (e.g. in the Gilbert cell).
- When used as a **switch** in the voltage mode, the MOSFET can be used to build *passive* mixers (e.g. a simple single-balanced mixer using only one MOSFET).
- A reasonably large enough **voltage swing** (a few 100 mV) is needed for driving the **switch**.
- Such passive mixers have signal loss.

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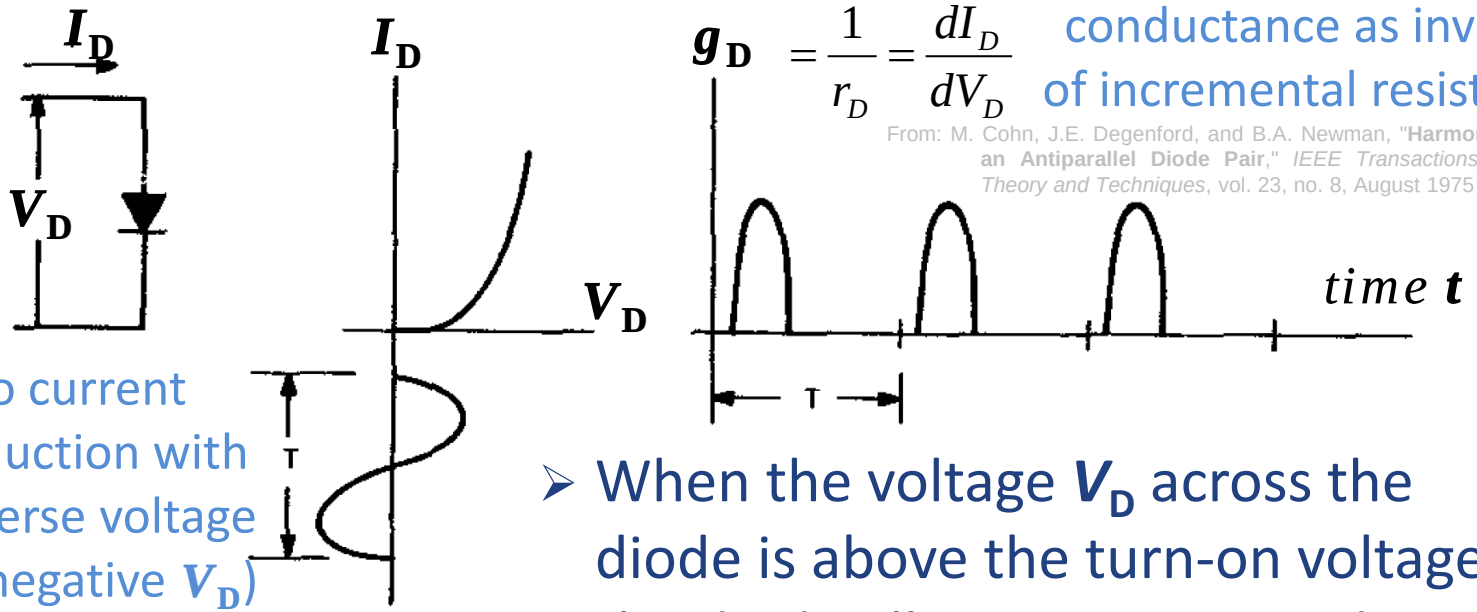
Diode as a Switch

(2-terminal device)

- Apart from the MOSFET (or other three-terminal devices), the two-terminal **diode** can also serve as a switch and hence it can be used to build a **mixer**.



From: M. Cohn, J.E. Degenford, and B.A. Newman, "**Harmonic Mixing with an Antiparallel Diode Pair**," *IEEE Transactions on Microwave Theory and Techniques*, vol. 23, no. 8, August 1975 (pp. 667-673).

no current conduction with a reverse voltage (i.e. negative V_D)

- When the voltage V_D across the diode is above the turn-on voltage, the diode allows current conduction.
- Do you know the turn-on voltages of typical diodes?

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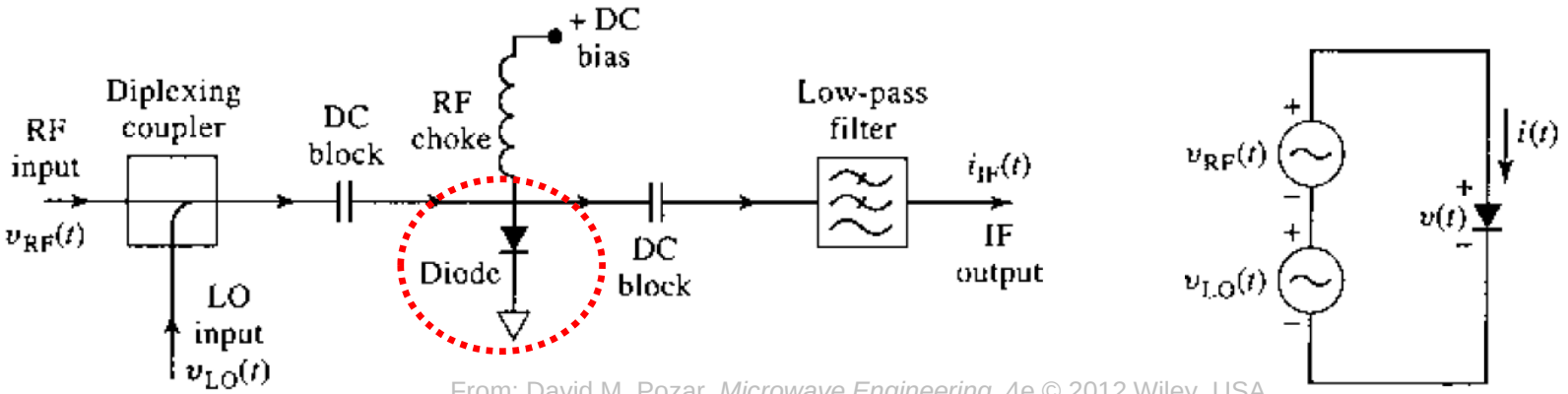
Diode Mixer

(single-balanced)

- A simple implementation of a **diode mixer** requires only one **diode** serving as the **switch**.



From: David M. Pozar, *Microwave Engineering*, 4e © 2012 Wiley, USA.

  - The LO signal $\boldsymbol{v}_{\mathbf{LO}}(t)$ is coupled with a small signal $\boldsymbol{v}_{\mathbf{RF}}(t)$ and then the signals added together will either turn on or off the diode $\Rightarrow$ **switching action**.
  - If the diode is turned on, the signals will go to ground.
  - If it is turned off, the signals will pass to the IF port.

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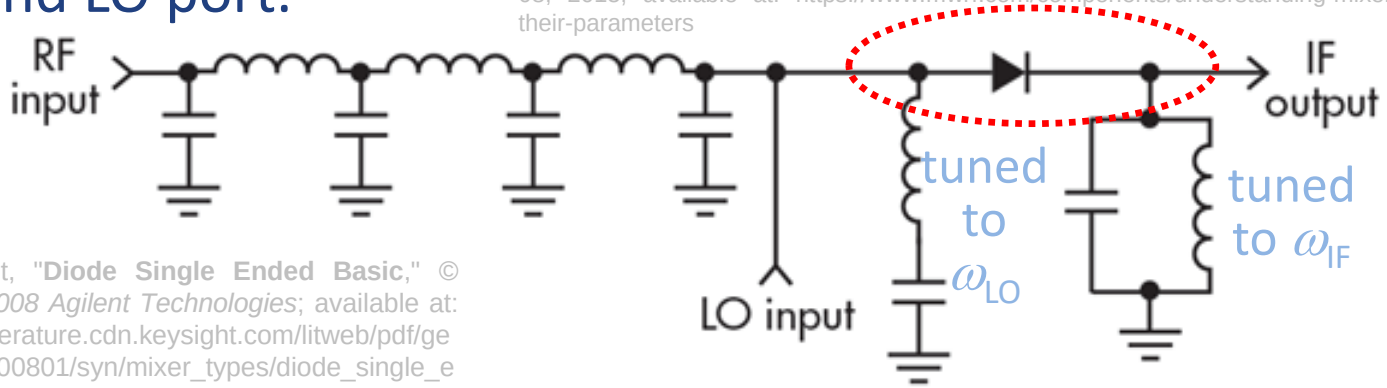
Diode Mixer

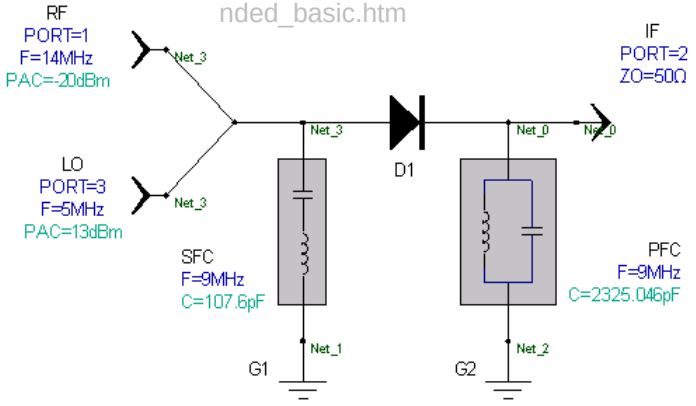
(diode in the signal path)

- A slightly different implementation has the diode connecting the RF port (and the LO port) to the IF port.
  - A passive LC network can be used to separate the RF port and LO port.

From: Chris DeMartino, "**Understanding Mixers and Their Parameters**," *Microwaves & RF*, July 08, 2015; available at: https://www.mwrf.com/components/understanding-mixers-and-their-parameters



From: Keysight, "**Diode Single Ended Basic**," © *1994-2008 Agilent Technologies*; available at: http://literature.cdn.keysight.com/litweb/pdf/genesys200801/syn/mixer_types/diode_single_ended_basic.htm



- The LO signal presumably has a large enough **voltage swing** to turn on or off the **diode** in such an design.

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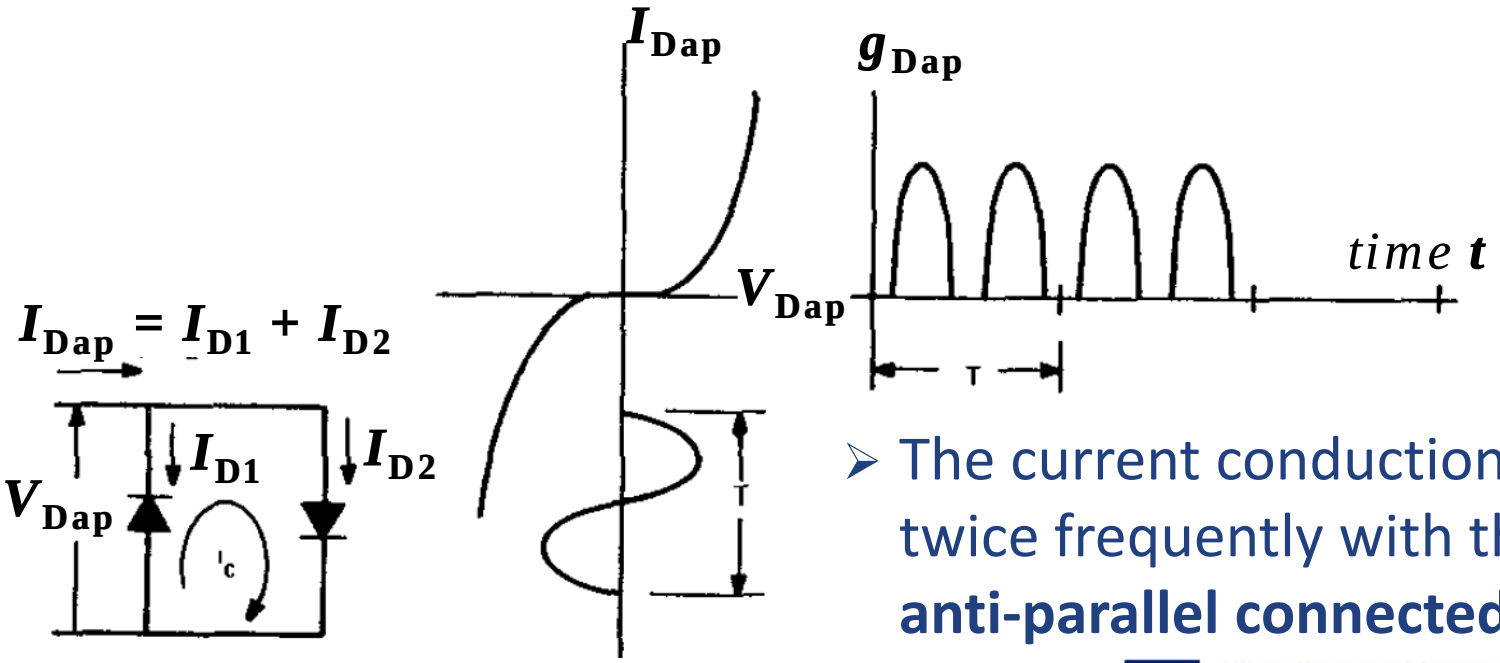
Diode as a Switch

(single-balanced signal)

- The **diode mixer** using only one diode can be improved to have a ***single-balanced*** LO signal for the **switching action**.
  - It is by the *anti-parallel* connection of two diodes.



- The current conduction is twice frequently with the **anti-parallel connected diodes**.

From: M. Cohn, J.E. Degenford, and B.A. Newman, "**Harmonic Mixing with an Antiparallel Diode Pair**," *IEEE Transactions on Microwave Theory and Techniques*, vol. 23, no. 8, August 1975 (pp. 667-673).

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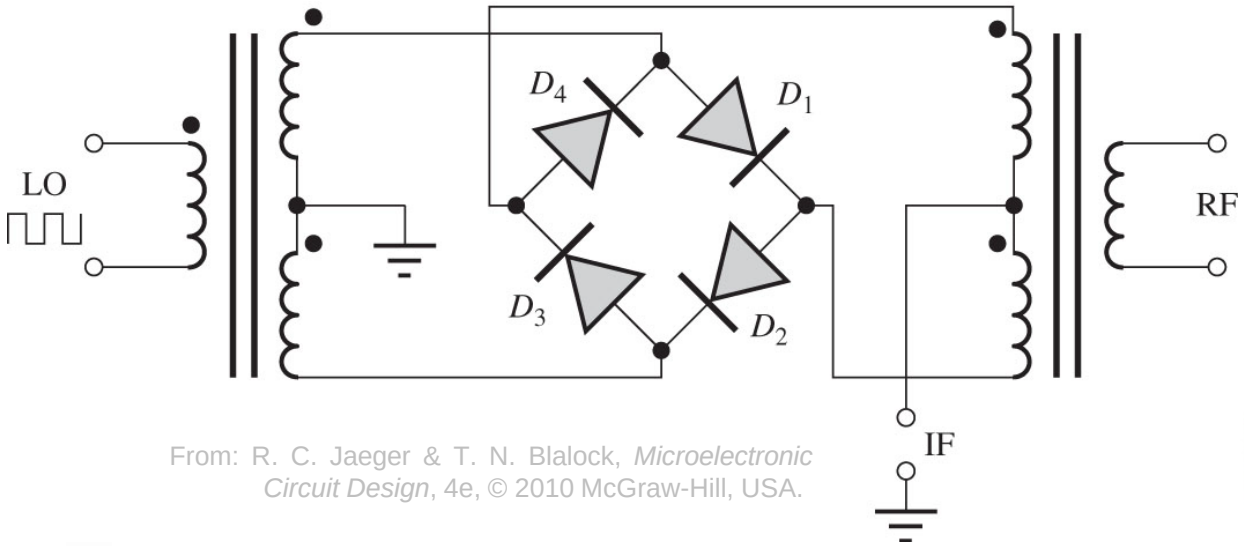
Double-Balanced Diode Mixer

(bridge configuration of 4 diodes)

- A double-balanced **diode mixer** can be obtained using a bridge configuration of four diodes. It is also called a ring design.
  - Transformers are needed to couple the balanced LO signal and also the balanced RF signal to the ring-connected diodes.



From: R. C. Jaeger & T. N. Blalock, *Microelectronic Circuit Design*, 4e, © 2010 McGraw-Hill, USA.

- The IF output can be tapped from either transformer for the LO or RF signals.

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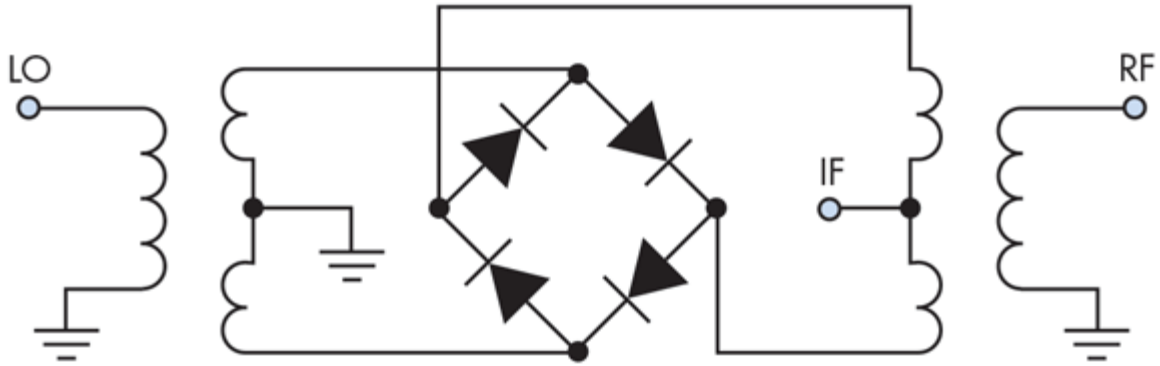
Double-Balanced Diode Mixer

(connection with single-ended signals)

- The double-balanced **diode mixer** can also be used in the single-balanced way (i.e. with the single-ended LO and RF signals).
  - In each of the transformers for the LO and RF signals, one terminal can simply be grounded.



From: Chris DeMartino, "**Understanding Mixers and Their Parameters**," *Microwaves & RF*, July 08, 2015; available at: https://www.mwrf.com/components/understanding-mixers-and-their-parameters

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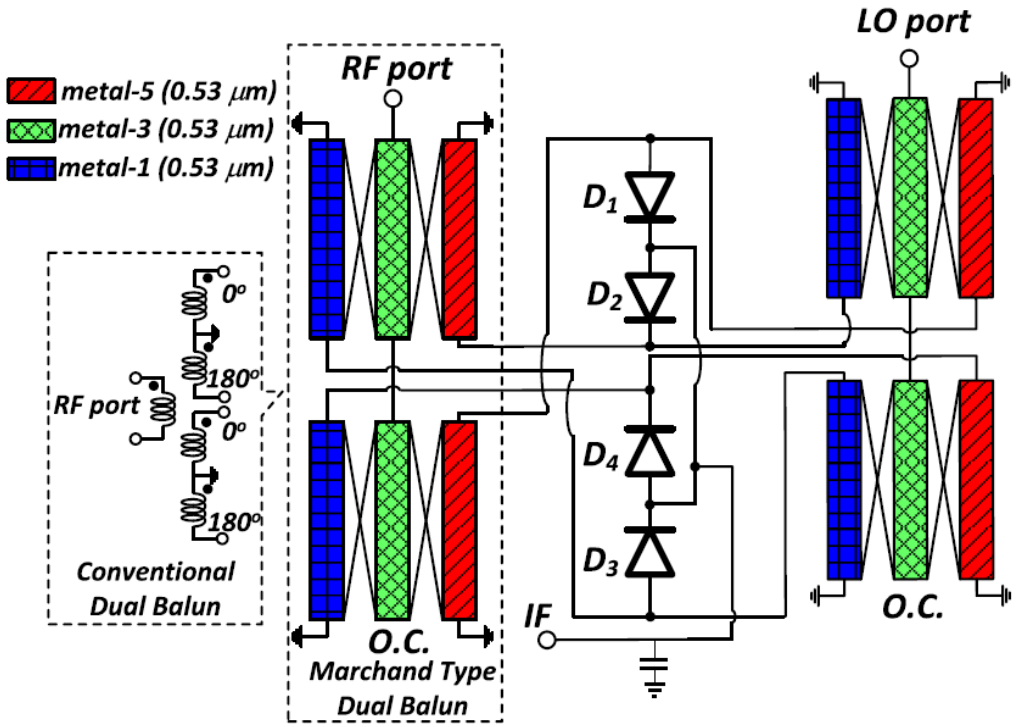
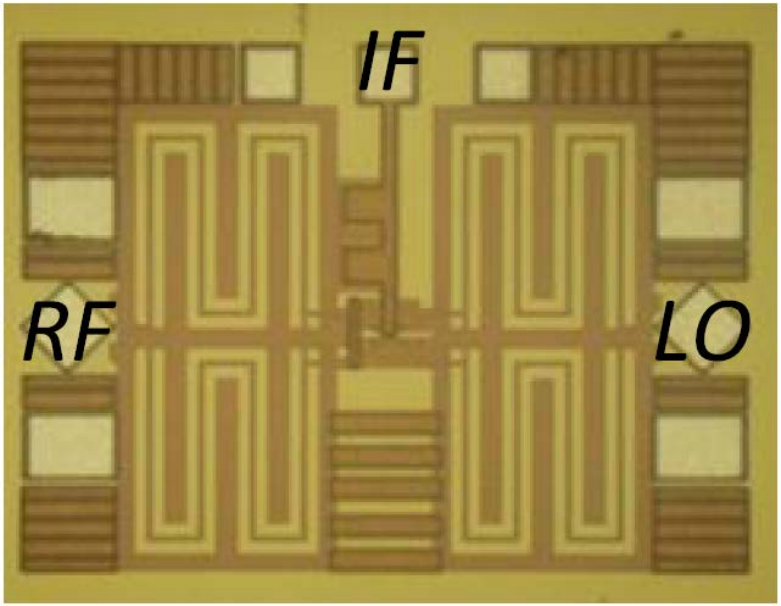
Double-Balanced Diode Mixer

(example in CMOS technology)

- The double-balanced **diode mixer** can be implemented in CMOS technology using Schottky diodes.



30GHz diode mixer in 0.18μm CMOS technology



From: Yu-Chih Hsiao *et al.*, "**Broadband CMOS Schottky-Diode Star Mixer Using Coupled-CPW Marchand Dual-Baluns**," *IEEE Microwave and Wireless Components Letters*, vol. 27, no. 5, May 2017 (pp. 500-502).

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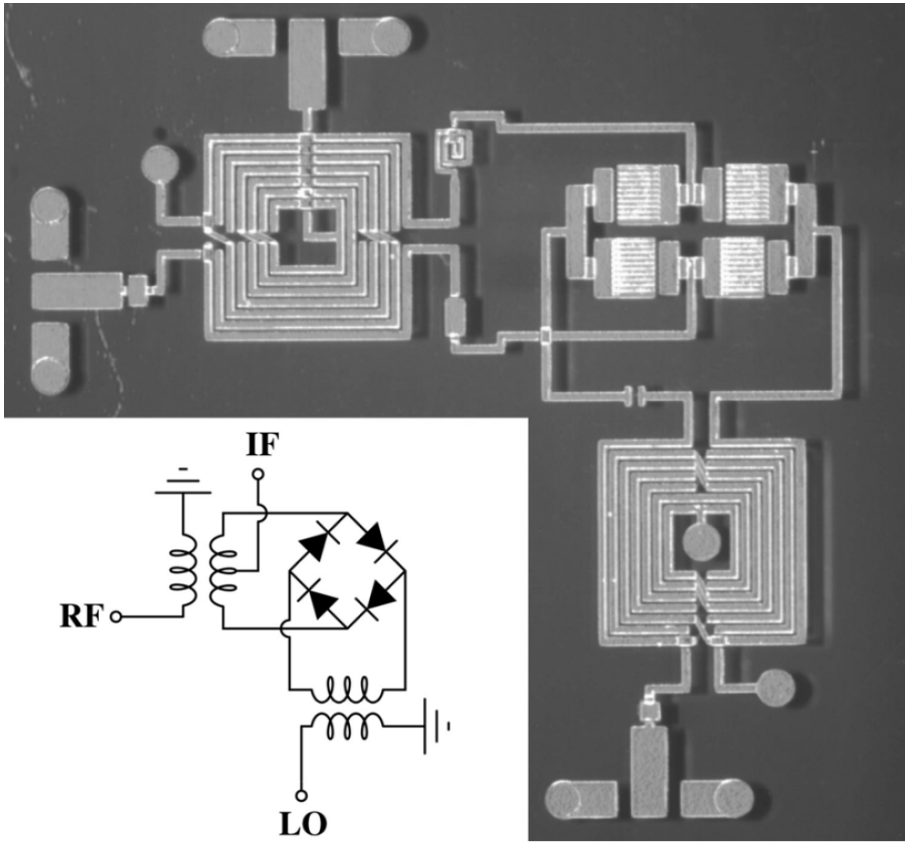
Double-Balanced Diode Mixer

(example using transformers)

- Transformers can be used in the diode mixers. Other types of Schottky diodes (e.g. silicon carbide) can be also used.



3.3GHz diode mixer using SiC Schottky diodes

From: M. Sudow, K. Andersson *et al.*, "**A highly linear double balanced Schottky diode S-band mixer**," *IEEE Microwave and Wireless Components Letters*, vol. 16, no. 6, June 2017 (pp. 336-338).

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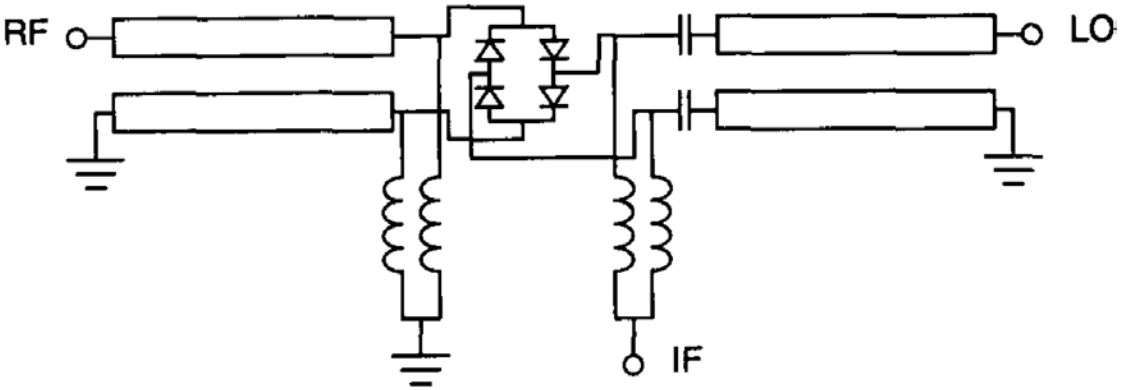
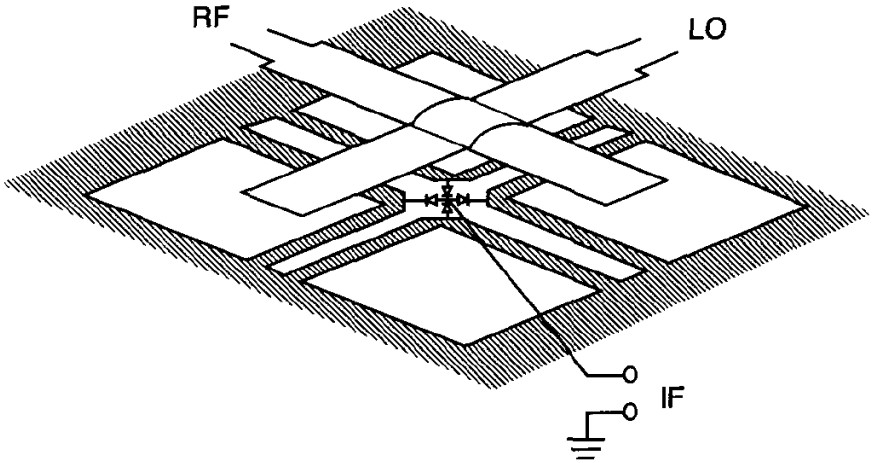
Double-Balanced Diode Mixer

(example using transformers)

- Transformers can be used in the diode mixers. Other types of Schottky diodes (e.g. silicon carbide) can be also used.





From: S.A. Maas and Kwo Wei Chang, "**A broadband, planar, doubly balanced monolithic Ka-band diode mixer**," *IEEE Transactions on Microwave Theory and Techniques*, vol. 41, no. 12, June 1993 (pp. 2330-2335).

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