Microwave Circuits and Sub-Systems

A2M17MOS

Narrow-Band Amplifier Design – Part A

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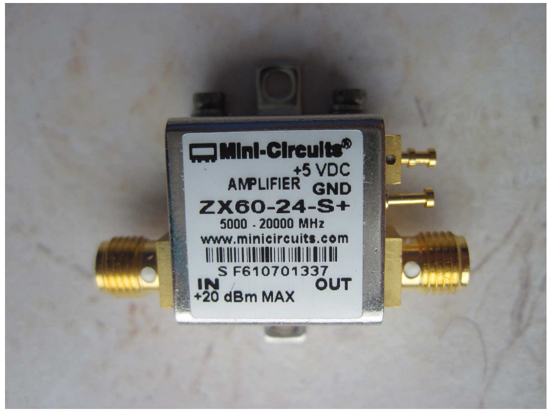
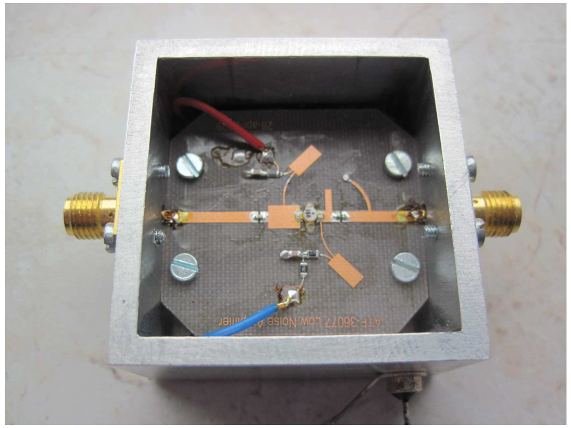
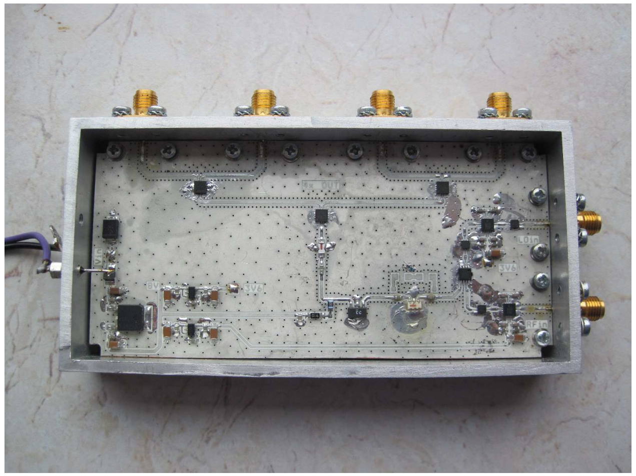
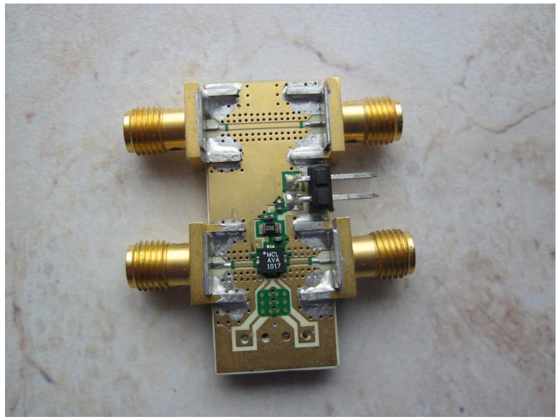
RF and Microwave Amplifiers



- Necessary for construction of RF & microwave systems
- Frequency range → commonly up to 100GHz
- Many different types of classification
- Based on RF & microwave transistors → BJT, HBT, MESFET, HEMT, …
- Different materials used → Si, GaAs, InP, GaN, …
- Different manufacturing technologies used

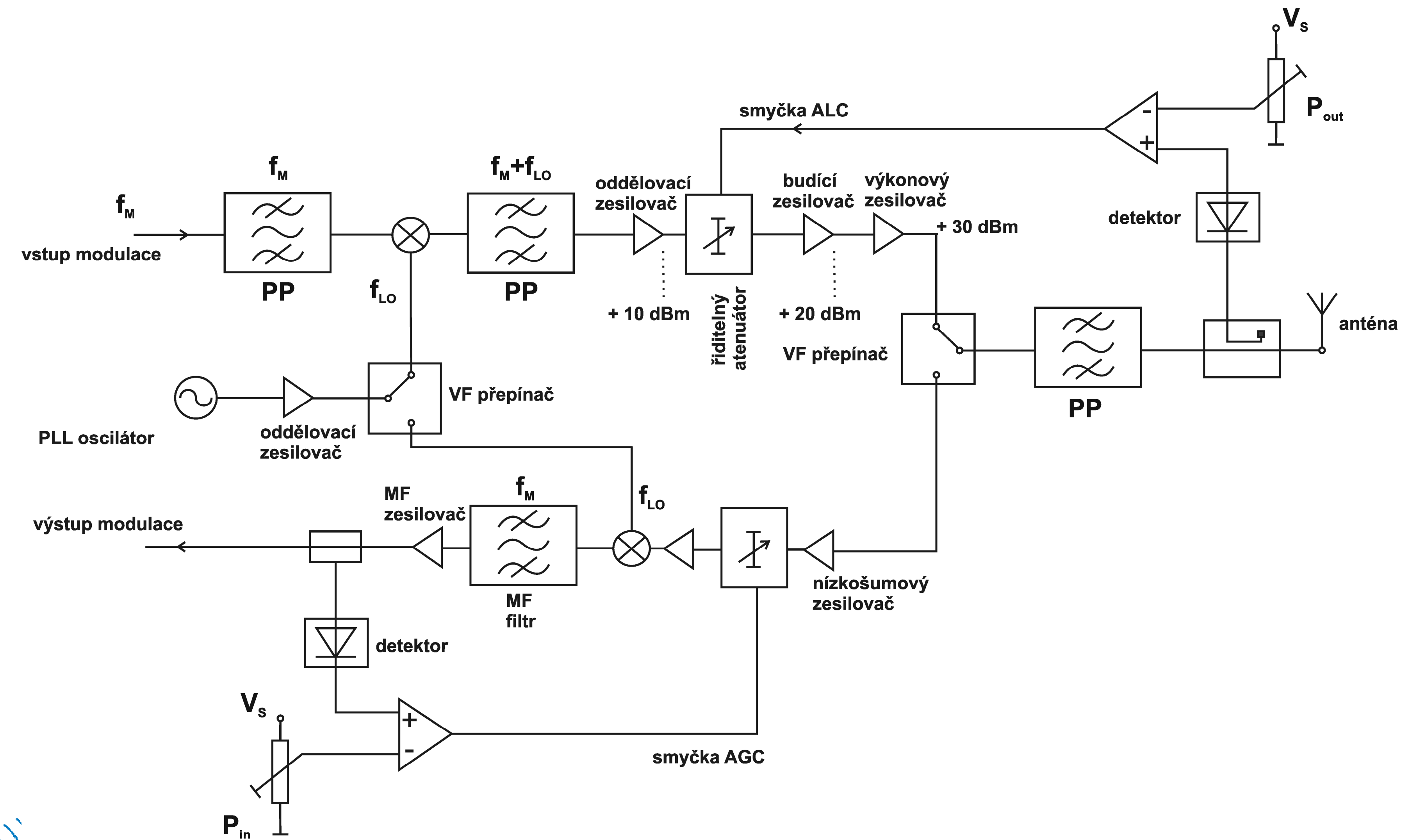






RF System - Example

TDMA transceiver with ALC and AGC loops



Classification

- **According to output power:**
  - **Low-power amplifiers**
    - Up to ≈10mW
    - Low-power transistors used, $I_{DS} \lesssim \approx 50mA$
    - Design → based on linear s-parameters, linear simulators can be employed
    - Application → general amplification stages
    - The most frequent amplifier type
  - **Medium-power amplifiers**
    - Up to ≈ 200 - 500mW
    - Medium-power transistors used, $I_{DS} \lesssim \approx 150mA$
    - Design → based on linear s-parameters, usually
    - Application → medium-power output stages, driver-stages of power amplifiers
  - **Power amplifiers**
    - $10^0 – 10^2$ W (only seldom more)
    - High-power transistors
    - Design → using non-linear simulators, large-signal models and non-linear measurement
    - Application → transmitter (communication, radar,…) power output stages
    - Can be very expensive

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Classification

- **According to frequency bandwidth:**
  - **Narrow-band amplifiers**
    - $B \leq 10\%$ of the center frequency f_0
    - Design → relatively simple, solution exists always, direct synthesis formulas
  - **Wide-band amplifiers**
    - $B \geq 10\%$ of the center frequency f_0, often 2-3 octaves
    - Example: 2-8 GHz, 10-18GHz
    - Design → can be very complicated, no solution can exist, approximations, iterations and computer optimizations must be employed
  - **Extremely wide-band amplifiers**
    - B often more decades
    - Examples: 0,01 – 8GHz, 1- 20GHz
    - Special structures → resistive matching, feedback amplifiers, distributed amplifiers

Classification

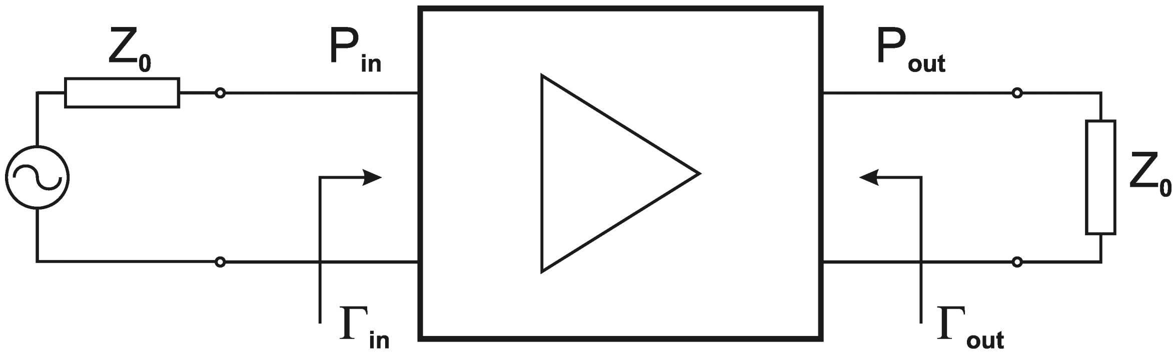
- **According to realization:**
  - With **absolutely stable** or **potentially unstable** transistors
  - With **lumped** (L,C) or **distributed** (microstrip, co-planar) matching elements
  - With **discrete** components or **integrated** (MMIC)
- **Special amplifiers:**
  - Low-noise amplifiers (LNA)
  - Logarithmic amplifiers
  - Variable-gain amplifiers
  - Complex amplifier structures → „Feed-Forward“, Doherty, …

Parameters

- Important parameters of RF & microwave amplifiers:

- **Gain** (insertion gain)
  - Defined by the output/input powers ratio $G = \frac{P_{out}}{P_{in}}$
  - Often stated in dB $G_{dB} = 10\log\frac{P_{out}}{P_{in}}$
- **Input and output reflections**
  - Generally described as Γ_{in} and Γ_{out}
  - Complex values → but often only modules are important

  - Modules can be expressed as RL or SWR $\left|\Gamma\right|_{dB} = RL = -20\log\left|\Gamma\right|$ $SWR = \frac{1+\left|\Gamma\right|}{1-\left|\Gamma\right|}$
  - AWR MS → S11, S22 or dBS11, dBS22



Parameters

- **Stability**
  - Refers both to the transistor and the completed amplifier
  - **Absolute stability** is beneficial
  - But also **potential un-stability** or **conditional stability**
  - Decisive for design procedures and amplifier parameters obtained
  - Must be considered in the whole frequency band where the transistor is active
  - Non-stability can lead to parasitic oscillations resulting in poor amplifier function or even in its destruction
- **Noise parameters**
  - Important in case of amplifiers processing very weak signals, typically amplifiers connected at inputs of radio receivers and processing signals from antennas
  - Defined by the noise figure F, or the noise temperature T_e
  - For the LNA design → additional 4 design noise parameters must be known
- **Non-linear parameters**
  - Important in case of amplifiers working with high-level signals
  - Common non-linear parameters: P_{-1dB}, IM2, IM3, IP2, IP3, …

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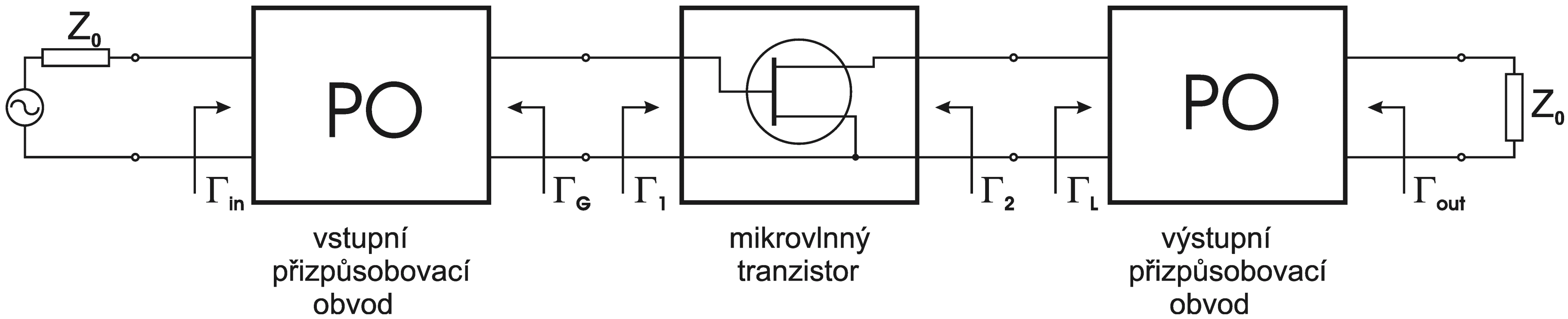
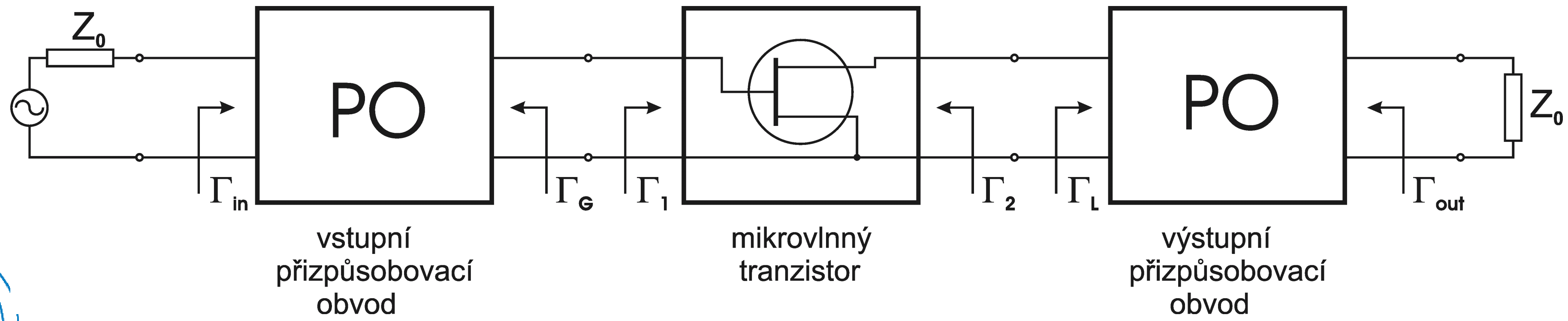
Basic Amplifier Structure

- Important design reflection coefficients:
  - Γ_1 — transistor input reflection coefficient with the Γ_L loading at output
  - Γ_2 — transistor output reflection coefficient with the Γ_G loading at input
  - Γ_G — reflection coefficient „seen“ by the transistor input (gate, base)
  - Γ_L — reflection coefficient „seen“ by the transistor output (drain, collector)
  - Γ_{in} — input reflection coefficient of the whole amplifier
  - Γ_{out} — output reflection coefficient of the whole amplifier



Basic Amplifier Structure

- Modules of s_{11} and s_{22} are too high usually
- That is why input and output **matching circuits** (MCs) are necessary
- The input MC transforms Z_0 to Γ_G
- The output MC transforms Z_0 to Γ_L
- The **optimum Γ_G and Γ_L values** can be calculated according to parameters of the transistor used and the required amplifier parameters
- For calculation of the suitable Γ_G and Γ_L values, several design formulas are necessary



Calculation of Γ_1

- s-parameters

$$b_1 = s_{11}a_1 + s_{12}a_2$$
$$b_2 = s_{21}a_1 + s_{22}a_2$$

- Load

$$a_2 = b_2.\Gamma_L \qquad b_2 = s_{21}a_1 + s_{22}b_2\Gamma_L$$

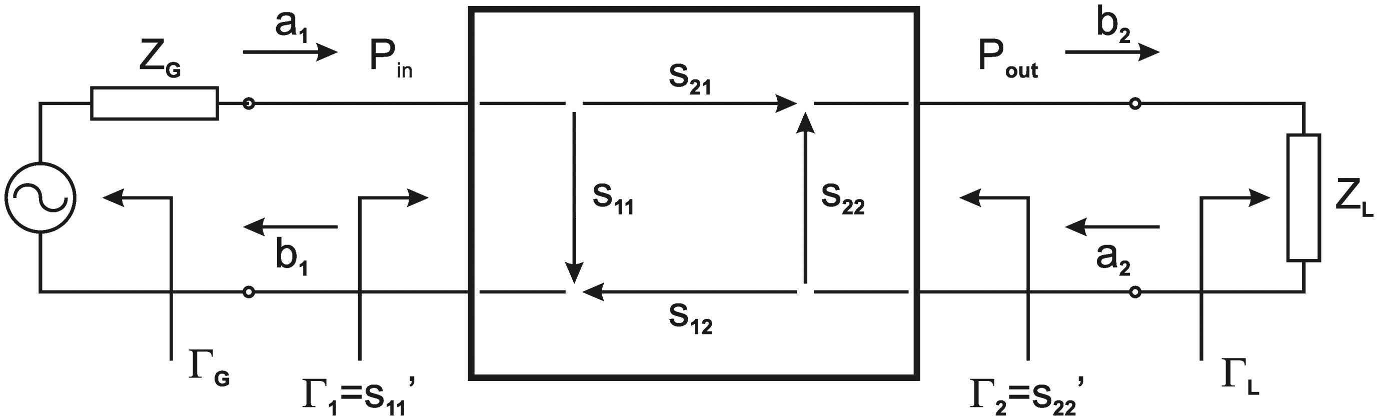
- From that

$$b_2 = \frac{s_{21}a_1}{1 - s_{22}\Gamma_L} \qquad a_2 = \Gamma_L \frac{s_{21}a_1}{1 - s_{22}\Gamma_L}$$

$$b_1 = s_{11}a_1 + s_{12}\Gamma_L \frac{s_{21}a_1}{1 - s_{22}\Gamma_L}$$

- Transformation formula

$$\Gamma_1 = s_{11}' = \frac{b_1}{a_1} = s_{11} + \frac{s_{12}s_{21}\Gamma_L}{1 - s_{22}\Gamma_L}$$



Calculation of Γ_2

- s-parameters

$$b_1 = s_{11}a_1 + s_{12}a_2$$
$$b_2 = s_{21}a_1 + s_{22}a_2$$

- Description of generator

$$a_1 = b_1.\Gamma_G \qquad b_1 = s_{11}b_1\Gamma_G + s_{12}a_2$$

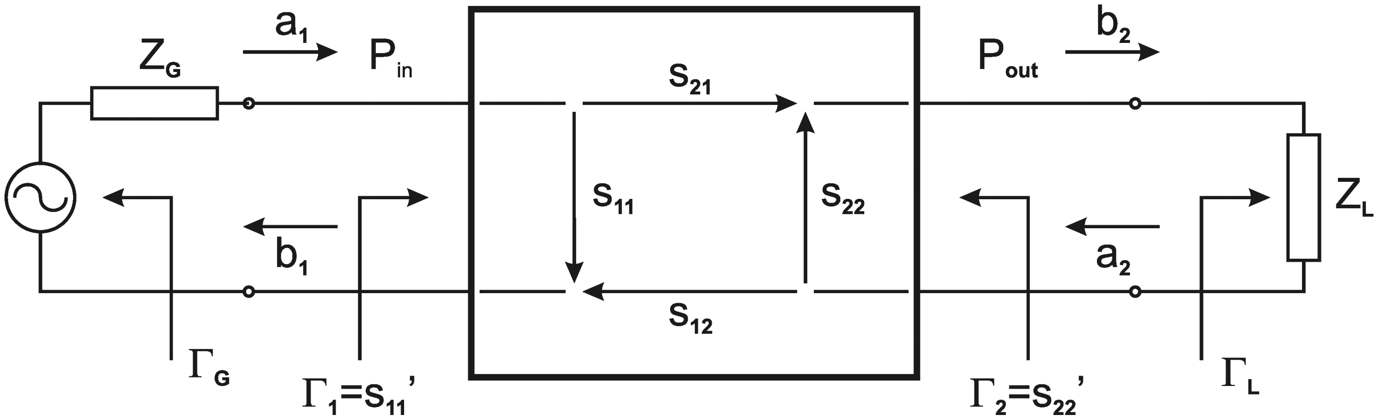
- From that

$$b_1 = \frac{s_{12}a_2}{1 - s_{11}\Gamma_G} \qquad a_1 = \Gamma_G \frac{s_{12}a_2}{1 - s_{11}\Gamma_G}$$

$$b_2 = s_{22}a_2 + s_{21}\Gamma_G \frac{s_{12}a_2}{1 - s_{11}\Gamma_G}$$

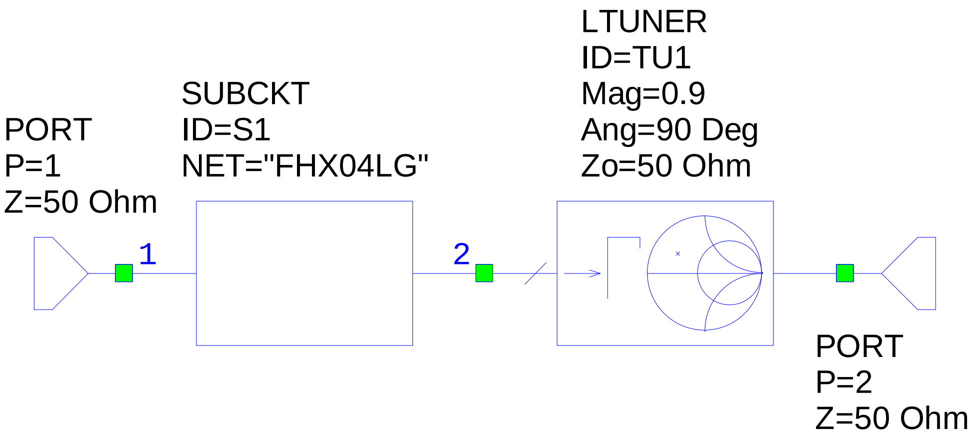
- Transformation formula

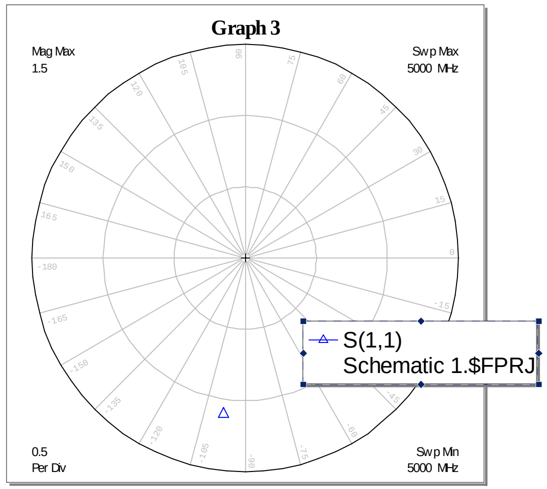
$$\Gamma_2 = s_{22}' = \frac{b_2}{a_2} = s_{22} + \frac{s_{12}s_{21}\Gamma_G}{1 - s_{11}\Gamma_G}$$



Remarks

- Transformation formula $$\Gamma_1 = s_{11}' = \frac{b_1}{a_1} = s_{11} + \frac{s_{12}s_{21}\Gamma_L}{1 - s_{22}\Gamma_L}$$
- Considering $\Gamma_L = 0$ $$\Gamma_1 = s_{11} + \frac{s_{12}s_{21}0}{1 - s_{22}0} = s_{11}$$
- s_{11} is defined with $\Gamma_L = 0$
- **AWR-MO:** Employment of the LTUNER model can be recommended
- **Example:** FHX04L → calculation of $\Gamma_1 = s_{11}'$ for $\Gamma_L = 0{,}9 / 90^0$





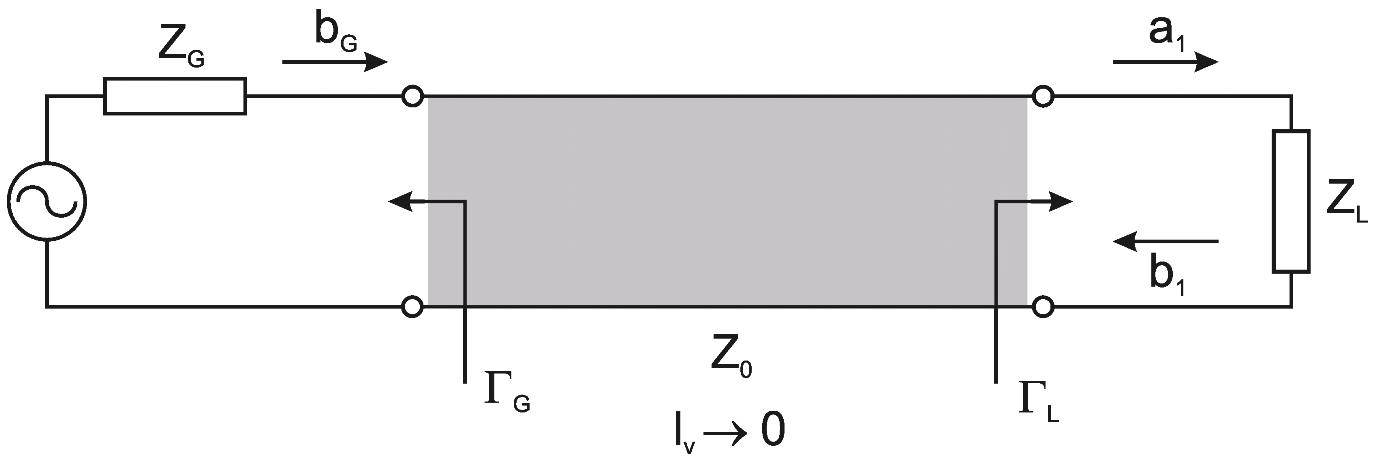
Connection of General Source and Load

- Connection of the source with **general reflection Γ_G with general load Γ_L**
- Both generator and load are **referred to the Z_0 impedance line**
- Impedance line Z_0 of a zero length is used for the inter-connection

- Description: $a_1 = b_G + b_1\Gamma_G$

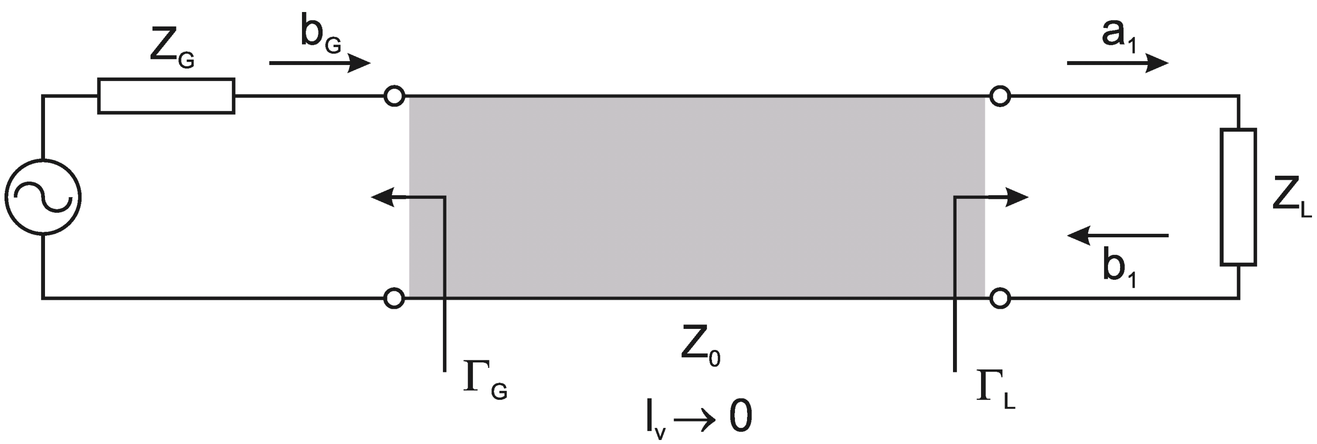
$$b_1 = a_1\Gamma_L \qquad a_1 = b_G + a_1\Gamma_G\Gamma_L$$

- $b_G \rightarrow$ incident voltage wave from Z_G into Z_0 $\qquad b_G = u_0 \dfrac{Z_0}{Z_G + Z_0}$



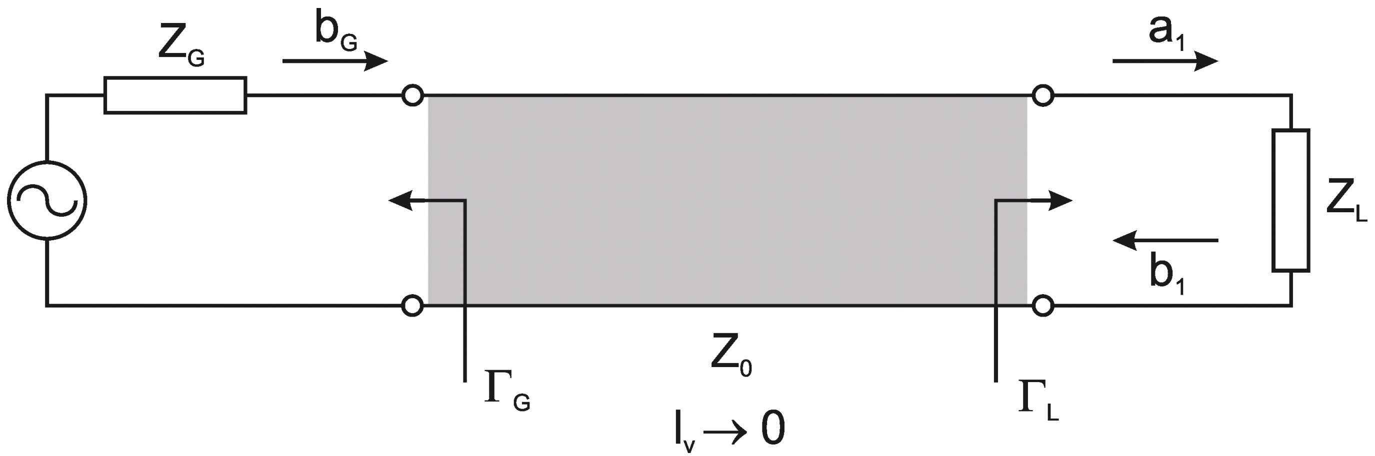
Power Delivered to Load - P_L

- Voltage waves a_i, b_i are normalized $a_i = u_i^+ / \sqrt{Z_0}$ $b_i = u_i^- / \sqrt{Z_0}$
- Power delivered to load: $P_L = |a_1|^2 - |b_1|^2 = |a_1|^2 \left(1 - |\Gamma_L|^2\right)$
- Incident wave $a_1 = b_G + a_1 \Gamma_G \Gamma_L$
- From that $a_1 = \dfrac{b_G}{1 - \Gamma_G \Gamma_L}$ $|a_1|^2 = \dfrac{|b_G|^2}{|1 - \Gamma_G \Gamma_L|^2}$
- Power delivered from the Γ_G source to the Γ_L load: $P_L = \dfrac{|b_G|^2 \left(1 - |\Gamma_L|^2\right)}{|1 - \Gamma_G \Gamma_L|^2}$



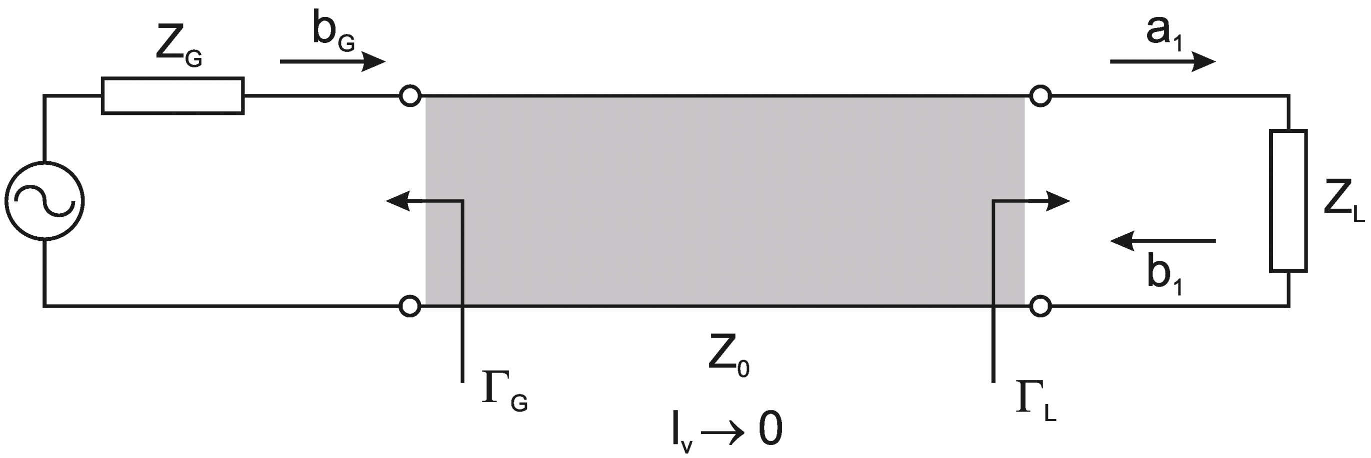
Power Available to Load - P_{AL}

- Power to the given load Γ_L from the optimized Γ_G
- Can be derived from the P_L using condition: $\Gamma_G = \Gamma_L^{*}$
- Power delivered to load: $$P_L = \frac{|b_G|^2 \left(1 - |\Gamma_L|^2\right)}{|1 - \Gamma_G \Gamma_L|^2}$$
- Power delivered from the $\Gamma_G = \Gamma_L^{*}$ source to the Γ_L load: $$P_{AL} = \frac{|b_G|^2 \left(1 - |\Gamma_L|^2\right)}{\left|1 - |\Gamma_L|^2\right|^2} = \frac{|b_G|^2}{1 - |\Gamma_L|^2}$$
- Condition – passive load: $|\Gamma_L| \le 1$



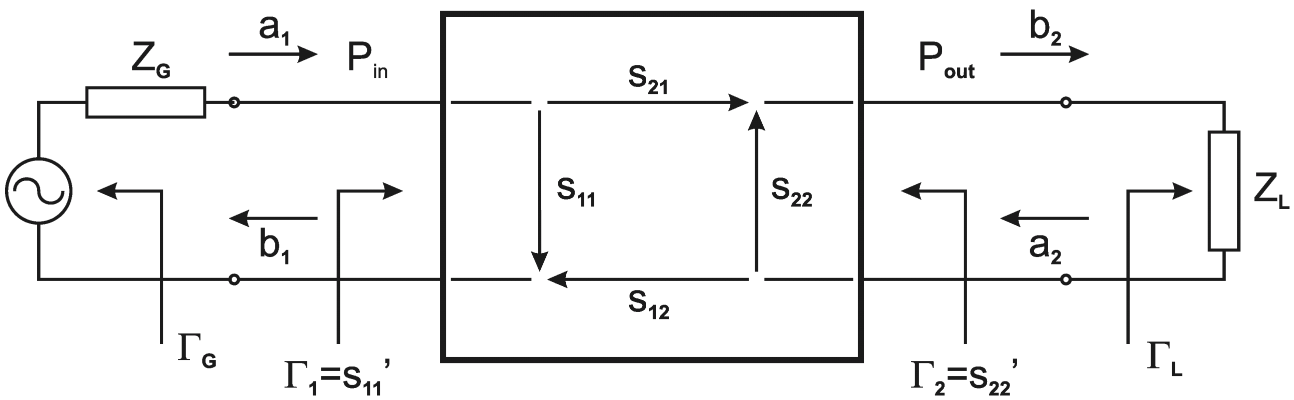
Power Available from Generator - P_{AG}

- Power from the given generator Γ_G to the optimized load Γ_L
- Can be derived from P_L using condition: $\Gamma_L = \Gamma_G^*$
- Power delivered to load: $P_L = \dfrac{|b_G|^2 \left(1 - |\Gamma_L|^2\right)}{|1 - \Gamma_G \Gamma_L|^2}$
- Power delivered from the Γ_G source to the $\Gamma_L = \Gamma_G^*$ load: $P_{AG} = \dfrac{|b_G|^2 \left(1 - |\Gamma_G^*|^2\right)}{|1 - \Gamma_G \Gamma_G^*|^2} = \dfrac{|b_G|^2}{1 - |\Gamma_G|^2}$
- Condition – passive load: $|\Gamma_G| \leq 1$



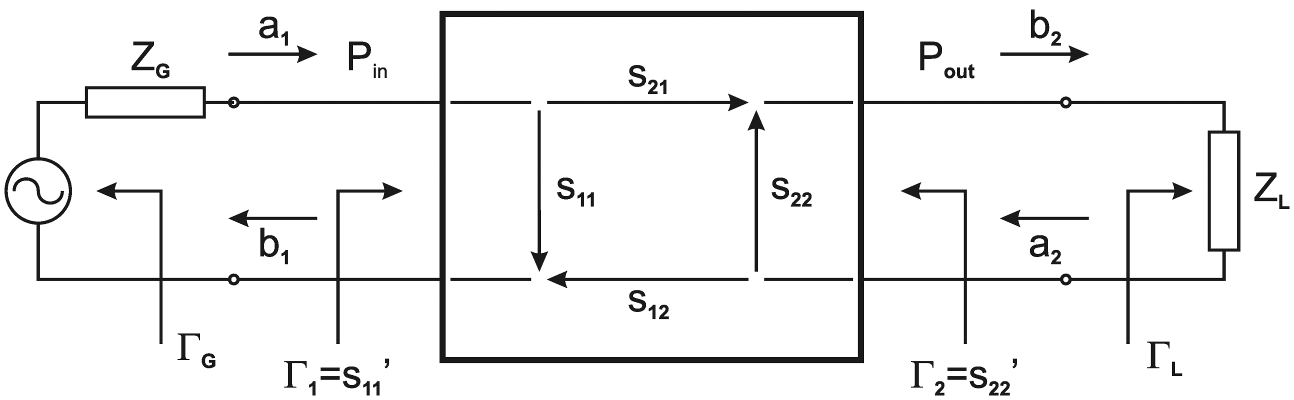
Transducer Gain - G_t

- The most general gain
- Depends upon s-parameters, Γ_G and Γ_L
- **Definition:** $$G_t = f(\Gamma_G, \Gamma_L, s_{ij}) = \frac{P_L}{P_{AG}}$$
- Using condition $a_2 = b_2\Gamma_L$, P_L can be expressed as: $$P_L = |b_2|^2 - |a_2|^2 = |b_2|^2 \left(1 - |\Gamma_L|^2\right)$$
- Available power from the generator: $$P_{AG} = \frac{|b_G|^2}{1 - |\Gamma_G|^2}$$
- From that: $$G_t = \frac{|b_2|^2}{|b_G|^2}\left(1 - |\Gamma_L|^2\right)\left(1 - |\Gamma_G|^2\right)$$



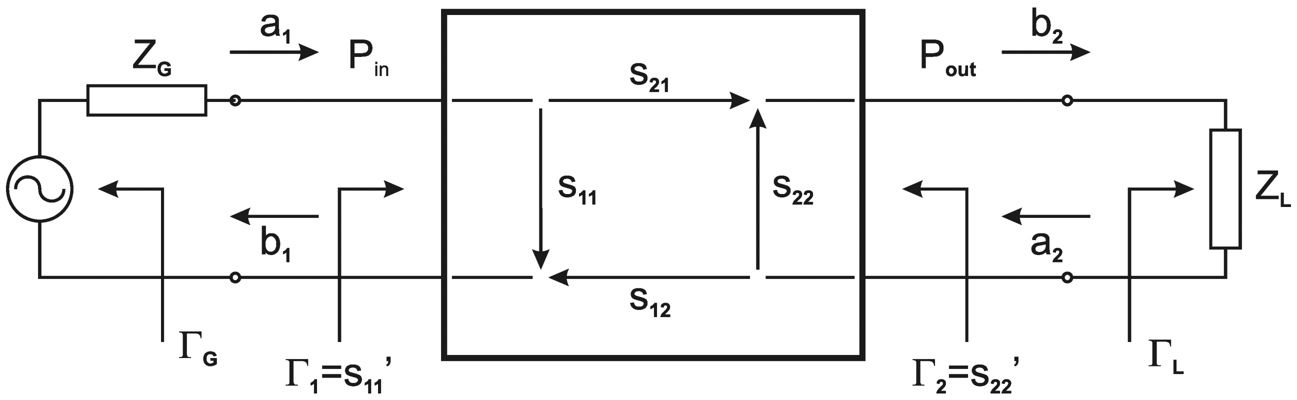
Transducer Gain - G_t

- Using $a_2 = b_2\Gamma_L$ and s-parameter definition: $b_2 = s_{21}a_1 + b_2 s_{22}\Gamma_L$
- From that: $b_2 = \dfrac{s_{21}a_1}{1-s_{22}\Gamma_L}$ $\qquad \dfrac{b_2}{a_1} = \dfrac{s_{21}}{1-s_{22}\Gamma_L}$
- Connection of Γ_G and Γ_1 : $a_1 = b_G + a_1\Gamma_G\Gamma_1$
- After re-arranging: $b_G = a_1(1-\Gamma_G\Gamma_1)$ $\qquad \dfrac{a_1}{b_G} = \dfrac{1}{1-\Gamma_G\Gamma_1}$
- From that: $\dfrac{b_2}{b_G} = \dfrac{b_2}{a_1}\dfrac{a_1}{b_G} = \dfrac{s_{21}}{1-s_{22}\Gamma_L}\dfrac{1}{1-\Gamma_G\Gamma_1}$ $\qquad \dfrac{|b_2|^2}{|b_G|^2} = \dfrac{|s_{21}|^2}{|1-s_{22}\Gamma_L|^2|1-\Gamma_1\Gamma_G|^2}$



Transducer Gain - G_t

- Transducer gain: $$G_t = \frac{|b_2|^2}{|b_G|^2}\left(1-|\Gamma_L|^2\right)\left(1-|\Gamma_G|^2\right)$$
- After substitution: $$G_t = \frac{|s_{21}|^2}{|1-s_{22}\Gamma_L|^2|1-\Gamma_1\Gamma_G|^2}\left(1-|\Gamma_L|^2\right)\left(1-|\Gamma_G|^2\right)$$
- Input reflection coeff.: $$\Gamma_1 = s_{11}' = \frac{b_1}{a_1} = s_{11} + \frac{s_{12}s_{21}\Gamma_L}{1-s_{22}\Gamma_L}$$
- Final expression: $$G_t = \frac{\left(1-|\Gamma_L|^2\right)|s_{21}|^2\left(1-|\Gamma_G|^2\right)}{|(1-s_{11}\Gamma_G)(1-s_{22}\Gamma_L)-s_{12}s_{21}\Gamma_G\Gamma_L|^2}$$

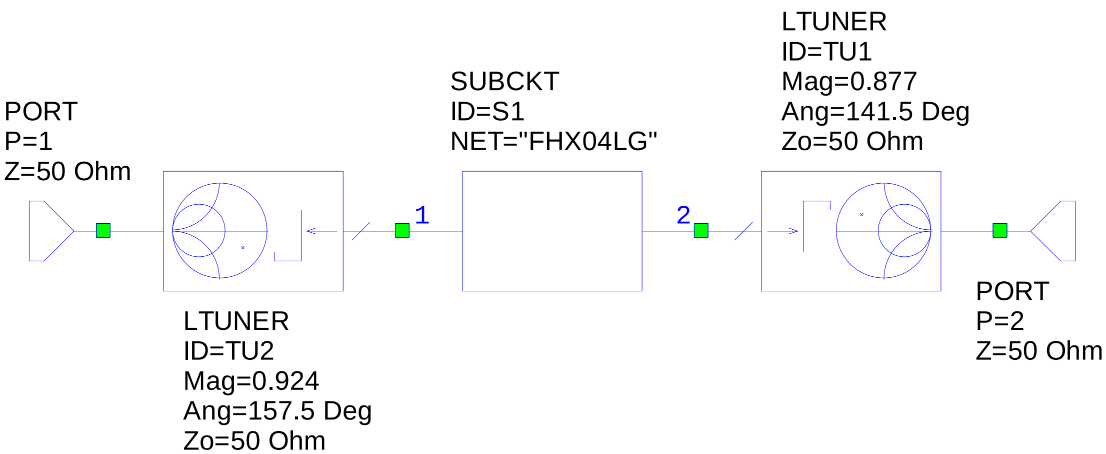


Remarks

- Transducer gain: $$G_t = \frac{\left(1-\left|\Gamma_L\right|^2\right)\left|s_{21}\right|^2\left(1-\left|\Gamma_G\right|^2\right)}{\left|(1-s_{11}\Gamma_G)(1-s_{22}\Gamma_L)-s_{12}s_{21}\Gamma_G\Gamma_L\right|^2}$$

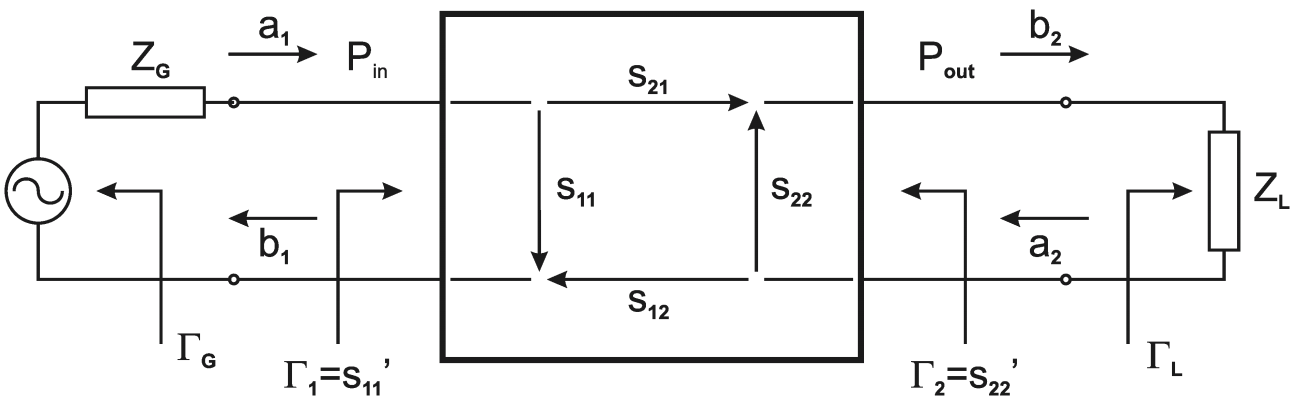
- Depends upon s-parameters, Γ_G and Γ_L $\quad G_t = f\left(\Gamma_G, \Gamma_L, s_{ij}\right)$
- The most general gain
- From G_t – many important gains can be derived

- Simulation by **AWR-MO** → 2x **LTUNER** models
- **Example:** Calculation of G_t for $\Gamma_G = 0{,}924 / 157{,}5^0$ and $\Gamma_G = 0{,}877 / 141{,}5^0$



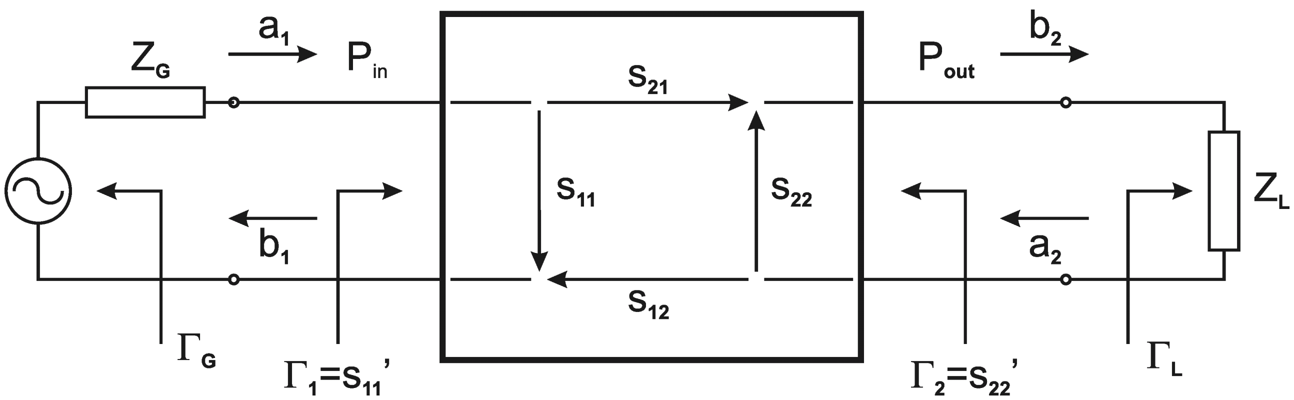
Power Gain - G_p

- Can be derived from the G_t using condition: $\Gamma_G = \Gamma_1^*$
- Final expression: $$G_P = \frac{\left(1-\left|\Gamma_L\right|^2\right)\left|s_{21}\right|^2}{\left|1-s_{22}\Gamma_L\right|^2\left(1-\left|\Gamma_1\right|^2\right)}$$
- Depends only on s-parameters and Γ_L
- Can be used only if perfect input matching is ensured
- Application: Design of amplifier using potentially unstable transistor
- Design task No.3
- **AWR-MO:** GP



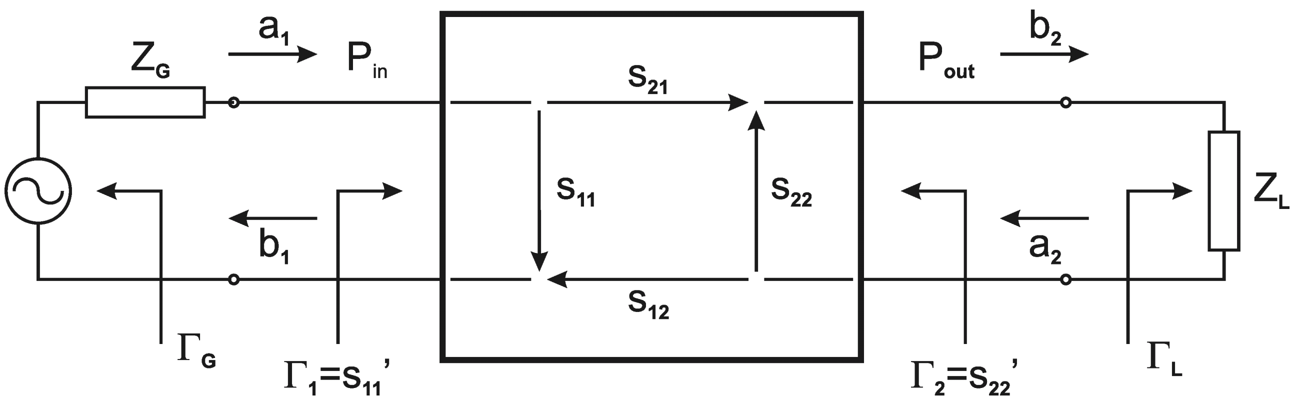
Available Gain - G_a

- Can be derived from the G_t using condition: $\Gamma_L = \Gamma_2^*$
- Final expression: $$G_a = \frac{(1-|\Gamma_G|^2)|s_{21}|^2}{|1-s_{11}\Gamma_G|^2(1-|\Gamma_2|^2)}$$
- Depends only on s-parameters and Γ_G
- Can be used only if perfect output matching is ensured
- Application: Design of low-noise amplifiers
- Design task No.4
- **AWR-MO:** GA



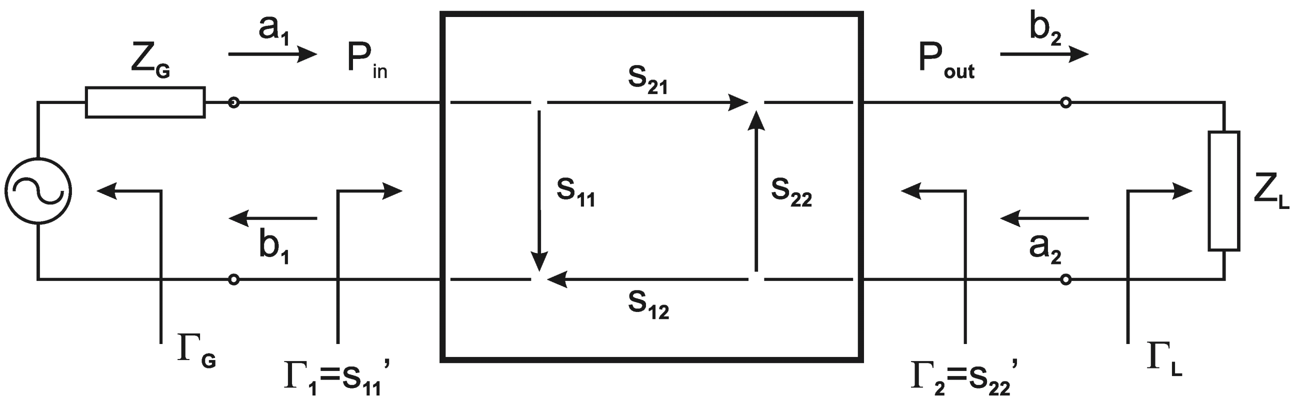
Maximum Available Gain - G_{amax}

- Can be derived from the G_t using both conditions: $\Gamma_L = \Gamma_2^*$ $\quad \Gamma_G = \Gamma_1^*$
- Final expression: $G_{a\max} = \left|\dfrac{s_{21}}{s_{12}}\right|(k - \sqrt{k^2 - 1})$
- Depends only on s-parameters, valid if simultaneous input and output matching can be ensured
- Valid only for absolutely stable transistors $k \geq 1$
- Represent the **best possible amplifier**, highest gain available from the given transistor at the given biasing point and frequency
- **AWR-MO:** GMax



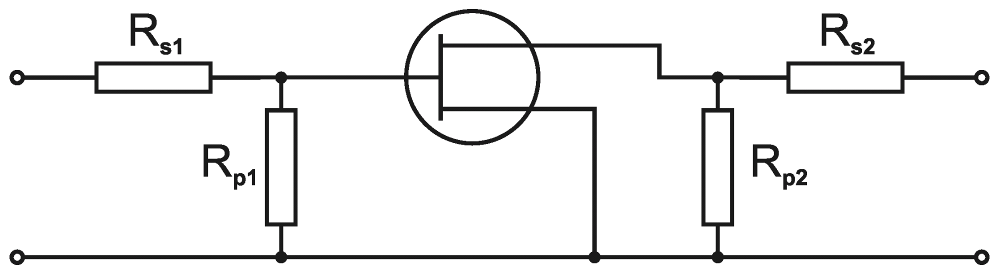
Unilateral Transducer Gain - G_{tu}

- Can be derived from the G_t using condition: $s_{12} = 0$
- Final expression: $G_{tu} = \dfrac{\left(1-\left|\Gamma_L\right|^2\right)\left|s_{21}\right|^2\left(1-\left|\Gamma_G\right|^2\right)}{\left|1-s_{22}\Gamma_L\right|^2\left|1-s_{11}\Gamma_G\right|^2}$
- G_{tu} can be divided into influence of the input MC, transistor and the output MC
- ATTENTION: Can lead to **wrong results**
- Usually, s_{12} is a small value → but in G_{tu} occurs in the $s_{12}.s_{21}$ product only !!!
- Cannot be easily neglected
- Recommendation: USE G_{tu} WITH HIGH CAUTION!!!



Maximum Stable Gain - G_{ms}

- Valid only for potentially unstable transistors: $k < 1$
- Final expression: $$G_{ms} = \left|\frac{s_{21}}{s_{12}}\right|$$
- Its **definition** is a bit unusual: Potentially unstable transistors with $k < 1$ can be stabilized using one or two external resistors. If the resistors ensure just $k = 1$, the corresponding gain is equal to G_{ms}.
- If transistor is operated with the G_{ms} gain:
  - Either the input reflection coefficient $|\Gamma_{in}| = 1$
  - Or the output reflection coefficient $|\Gamma_{out}| = 1$
- That is why practical operational gain must be **lower than G_{ms}** (min. by 1-2 dB)
- Application: Design of amplifiers with potentially unstable transistors
- **AWR-MO:** GMS
- Design task No.3b



Gain Directly to Z_0 – G_{tZ0}

- Gain of the 2-port connected directly to the Z_0 lines at input and output

- Final expression: $G_{tZ0} = |s_{21}|^2$

- Two important cases:
  - **Transistor** → G_{tZ0} represents gain without any matching circuits connected directly to Z_0 (can be high enough, but show unacceptable reflections)
  - **Amplifier** → G_{tZ0} represents real operational gain - amplifiers are operated into Z_0
- **AWR-MO:** G_{tZ0} [dB]=dBs21