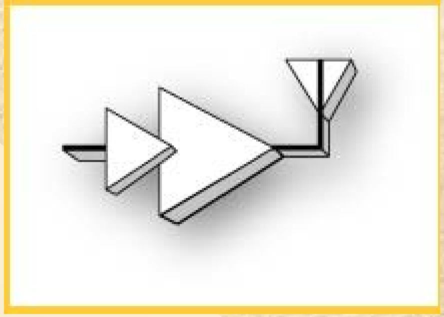
2009 Radio and Wireless Week

Power Amplifier Symposium



HIGH-EFFICIENCY RF AND MICROWAVE POWER AMPLIFIERS: HISTORICAL ASPECT AND MODERN TRENDS

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HIGH-EFFICIENCY
RF AND MICROWAVE POWER AMPLIFIERS:
HISTORICAL ASPECT AND MODERN TRENDS

I. POLYHARMONIC CLASS F AND INVERSE CLASS F POWER AMPLIFIERS

II. SWITCHED-MODE CLASS E POWER AMPLIFIERS

III. SWITCHED-MODE CLASS FE POWER AMPLIFIERS

POLYHARMONIC CLASS F AND INVERSE CLASS F POWER AMPLIFIERS

1. Class F: biharmonic and polyharmonic operation modes

2. Class F with quarterwave transmission line

3. Class F : load networks with lumped elements and transmission lines

4. Class F: LDMOSFET power amplifier design examples

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8. Practical high-efficiency Class F power amplifiers

1. Class F: biharmonic and polyharmonic operation modes

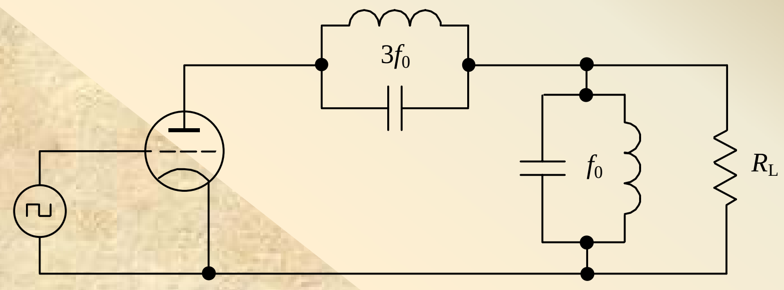
Fourier series for:

rectangular voltage waveform

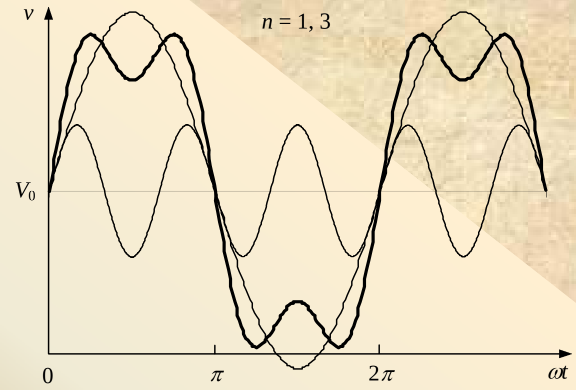
$$\frac{v(\omega t)}{V_0} = 1 + \frac{4}{\pi}\sin\omega t + \frac{4}{3\pi}\sin 3\omega t + \frac{4}{\pi}\sum_{n=5,7,...}^{N}\frac{\sin n\omega t}{n}$$

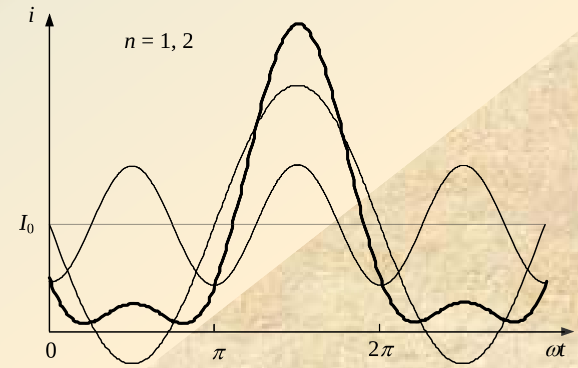
half-sinusoidal current waveform

$$\frac{i(\omega t)}{I_0} = 1 - \frac{\pi}{2}\sin\omega t - \frac{2}{3}\cos 2\omega t - 2\sum_{n=4,6,...}^{N}\frac{\cos n\omega t}{n^2-1}$$



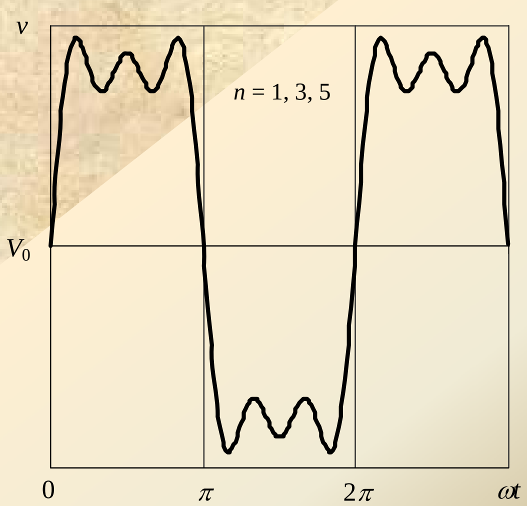
Third-harmonic peaking

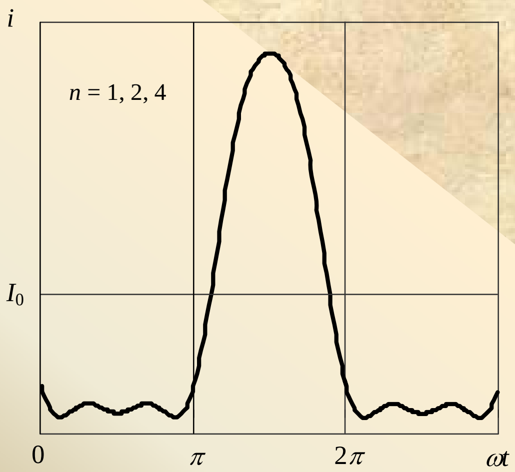


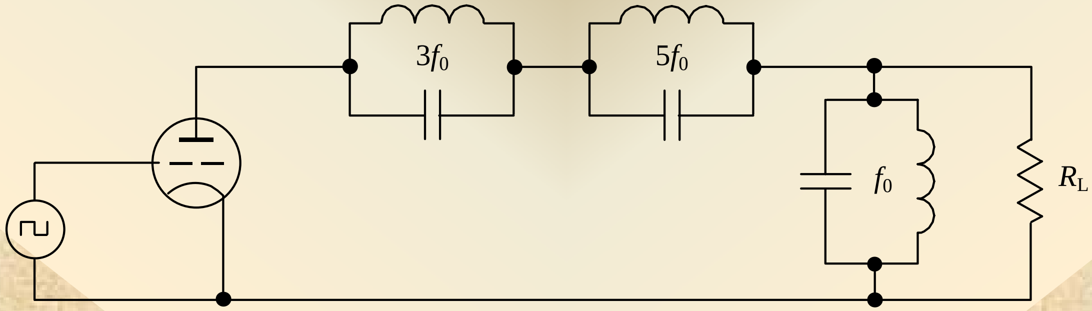


D. C. Prince, "Vacuum Tubes as Power Oscillators, Part III," *Proc. IRE*, vol. 11, pp. 527-550, Sept. 1923

1. Class F: biharmonic and polyharmonic operation modes





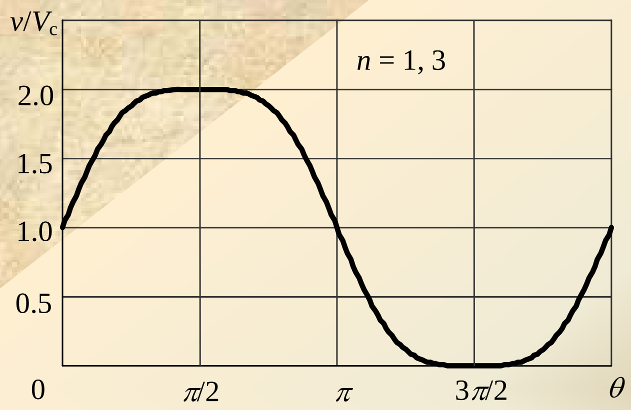


H. J. Round, "Wireless Telegraph and Telephone Transmission," U.S. Patent 1,564,627, Dec. 1925

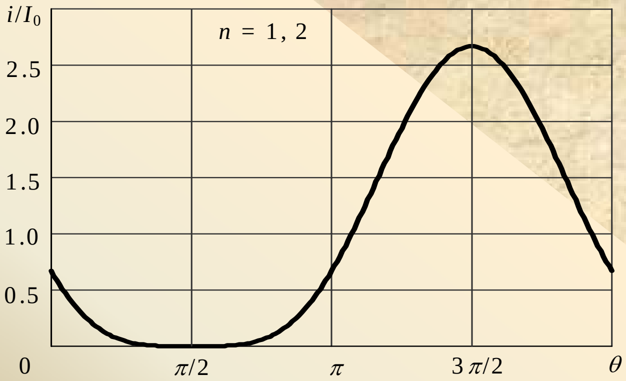
1. Class F: biharmonic and polyharmonic operation modes

For maximally flat waveforms

collector voltage



collector current



$$V_1 = \frac{9}{8} V_{cc} \qquad V_3 = \frac{1}{8} V_{cc}$$

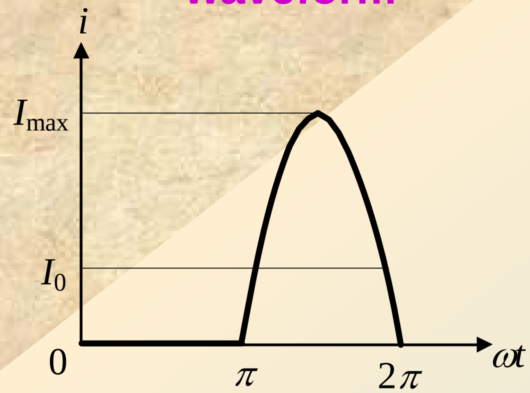
optimum values

$$I_1 = \frac{4}{3} I_0 \qquad I_2 = \frac{1}{3} I_0$$

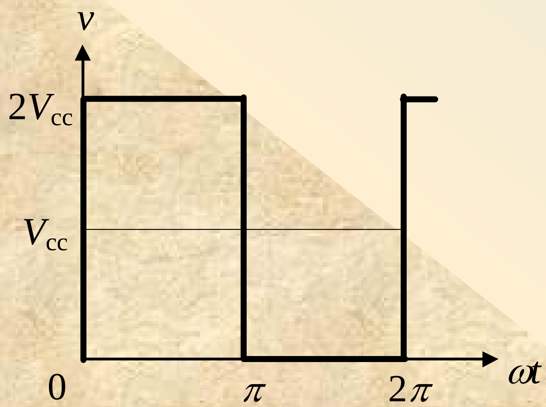
Current harmonic components	Voltage harmonic components				
	1	1, 3	1, 3, 5	1, 3, 5, 7	1, 3, 5, …, ∞
1	1/2 =0.500	9/16 = 0.563	75/128 = 0.586	1225/2048 = 0.598	2/π = 0.637
1, 2	2/3 = 0.667	3/4 = 0.750	25/32 = 0.781	1225/1536 = 0.798	8/3π = 0.849
1, 2, 4	32/45 = 0.711	4/5 = 0.800	5/6 = 0.833	245/288 = 0.851	128/45π = 0.905
1, 2, 4, 6	128/175 = 0.731	144/175 = 0.823	6/7 = 0.857	7/8 = 0.875	512/175π = 0.931
1, 2, 4,…, ∞	π/4 = 0.785	9π/32 = 0.884	75π/256 = 0.920	1225π/4096 = 0.940	1 = 1.000

1. Class F: idealized operation mode

Ideal current waveform



Ideal voltage waveform



$$I_1 = \frac{I_{max}}{2}$$ - *fundamental current component*

$$V_1 = \frac{4V_{cc}}{\pi}$$ - *fundamental voltage component*

$$I_0 = \frac{I_{max}}{\pi}$$ - *dc current component*

$$P_1 = \frac{V_{cc} I_{max}}{\pi}$$ - *fundamental output power*

$$P_0 = V_{cc} I_0$$ - *dc supply power*

$$\eta = \frac{P_1}{P_0} = 100\%$$ - *collector/drain efficiency*

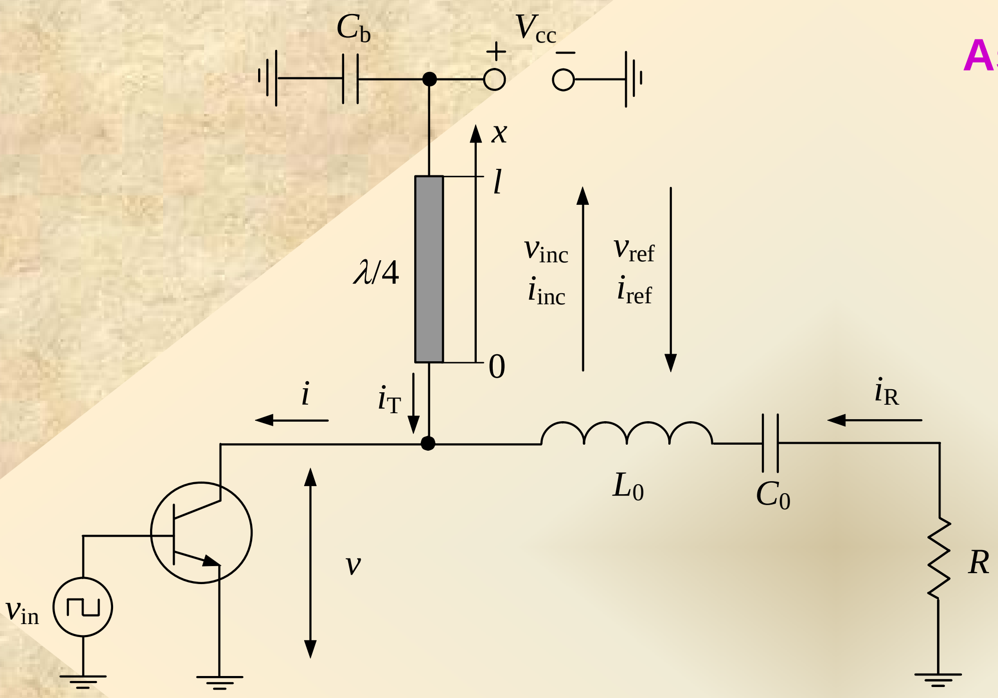
Harmonic impedance conditions:

$$Z_1 = R_1 = \frac{8}{\pi}\frac{V_{cc}}{I_{max}} = \frac{8}{\pi^2}\frac{V_{cc}}{I_0}$$

$$Z_n = 0 \quad \text{for even } n$$

$$Z_n = \infty \quad \text{for odd } n$$

2. Class F with quarterwave transmission line



Assumptions for transistor:

- ***ideal switch:*** ***no parasitic elements***
- ***half period is on, half period is off: 50% duty cycle***

Assumptions for load:

- ***sinusoidal current: ideal L_0C_0-circuit tuned to fundamental***

$$i(\omega t) = I_R \sin\omega t$$ ***- load current***

$$v(\omega t) = 2V_{cc} - v(\omega t + \pi)$$

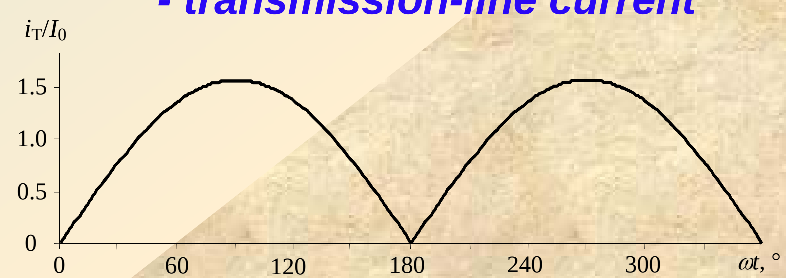
- collector voltage

$$i(\omega t) = I_R(\sin\omega t + |\sin\omega t|)$$

- collector current

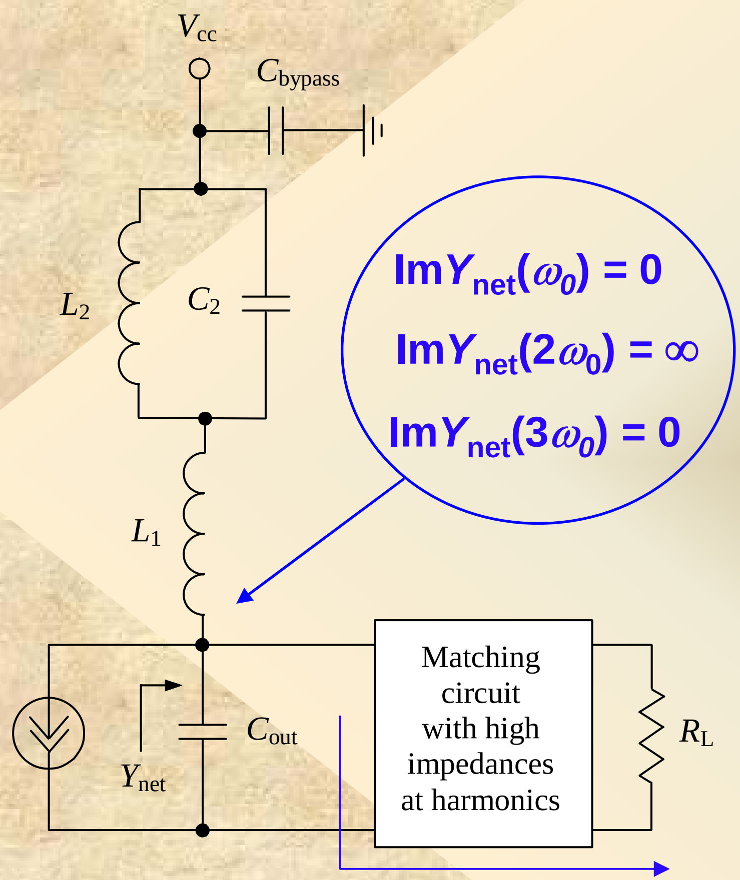
$$i_T(\omega t) = i_T(\omega t + \pi) = I_R|\sin\omega t|$$

- transmission-line current



3. Class F: second current and third voltage harmonic peaking

Load network



Circuit parameters

$$L_1 = \frac{1}{6\omega_o^2 C_{out}}, \quad L_2 = \frac{5}{3} L_1, \quad C_2 = \frac{12}{5} C_{out}$$

Output reactive admittance:

$$\mathrm{Im}(Y_{net}) = \omega C_{out} - \frac{1 - \omega^2 L_2 C_2}{\omega L_1 \left(1 - \omega^2 L_2 C_2\right) + \omega L_2}$$

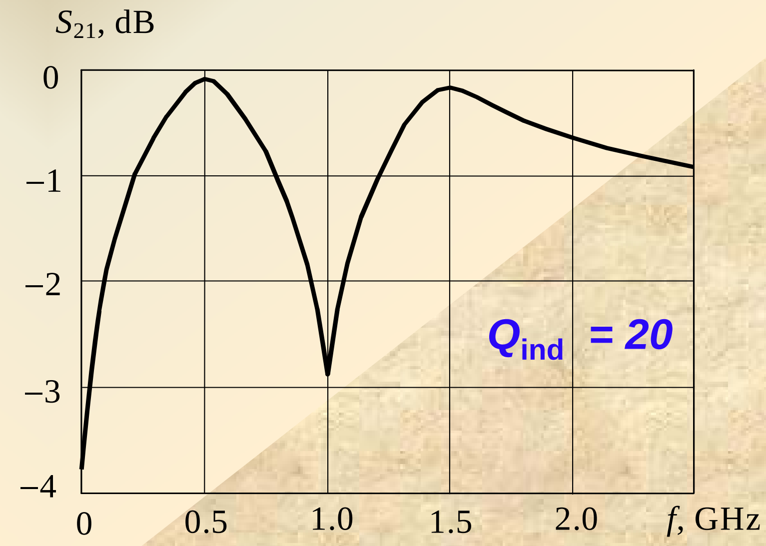
Three harmonic impedance conditions:

$$\left(1 - \omega_0^2 L_1 C_{out}\right)\left(1 - \omega_0^2 L_2 C_2\right) - \omega_0^2 L_2 C_{out} = 0$$

$$L_1\left(1 - 4\omega_0^2 L_2 C_2\right) + L_2 = 0$$

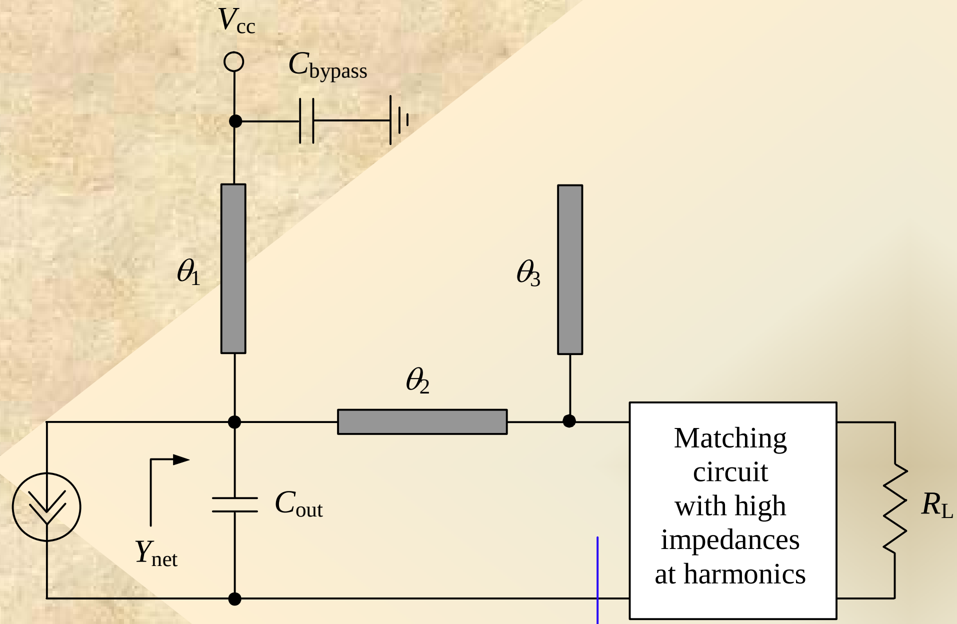
$$\left(1 - 9\omega_0^2 L_1 C_{out}\right)\left(1 - 9\omega_0^2 L_2 C_2\right) - 9\omega_0^2 L_2 C_{out} = 0$$

S_{21} simulation (f_0 = 500 MHz)



3. Class F: even current and third voltage harmonic peaking

Load network



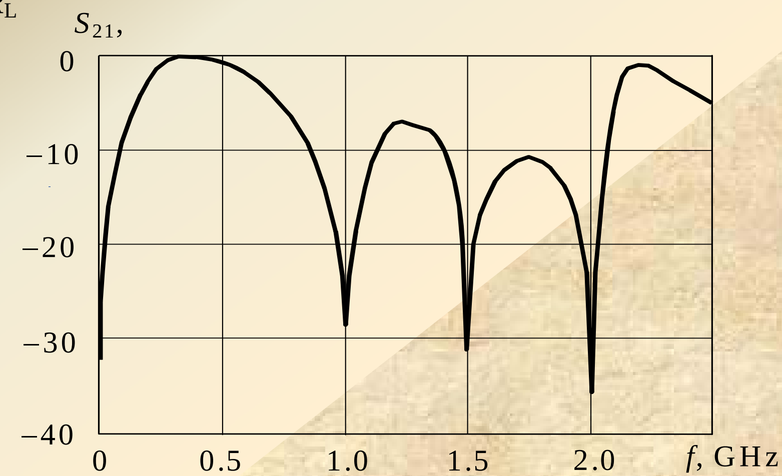
Harmonic impedance conditions at collector (drain):

Im$Y_{net}(\omega_0)$ = 0

Im$Y_{net}(2n\omega_0)$ = ∞

Im$Y_{net}(3\omega_0)$ = 0

S_{21} simulation (f_0 = 500 MHz)



Circuit parameters:

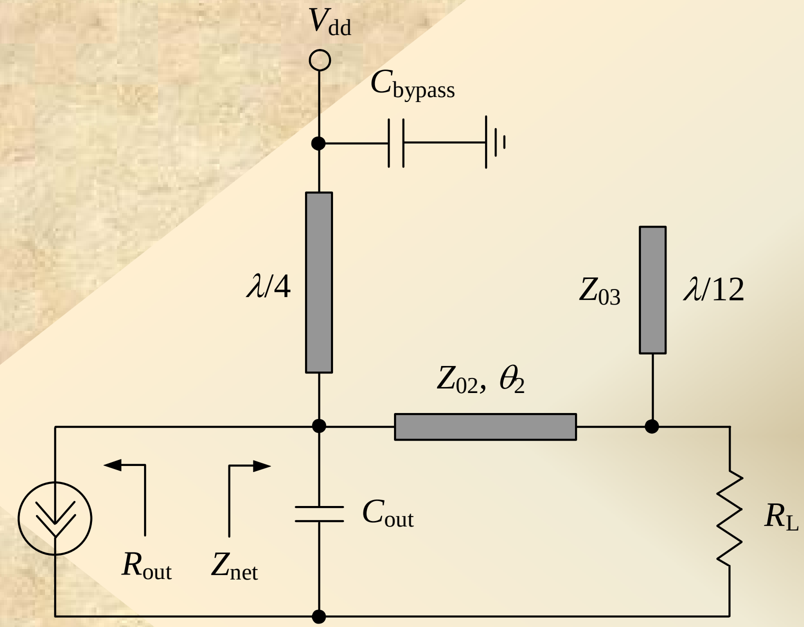
$$\theta_1 = \frac{\pi}{2}, \quad \theta_3 = \frac{\pi}{6}$$

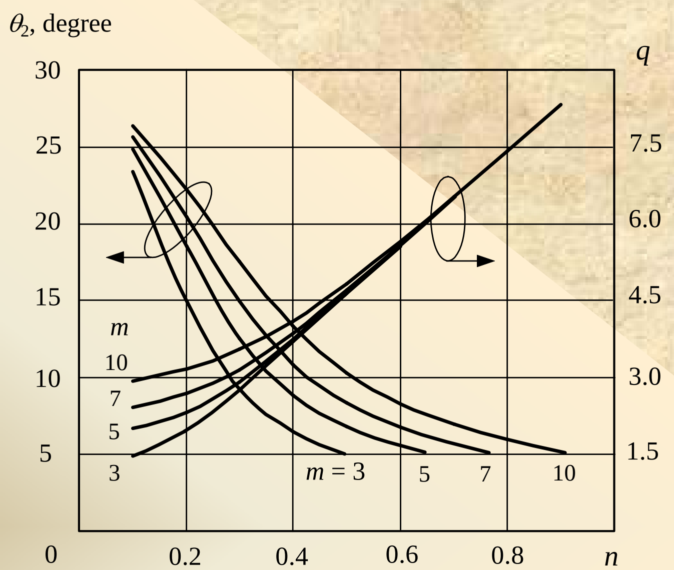
$$\theta_2 = \frac{1}{3}\tan^{-1}\left(\frac{1}{3Z_0\omega C_{out}}\right)$$

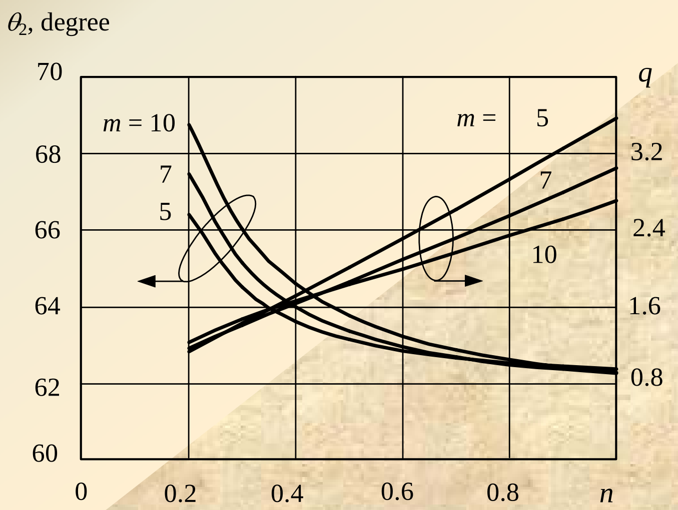
➢ ***ideal transmission lines***

3. Class F: even current and third voltage harmonic peaking

Load network with impedance matching







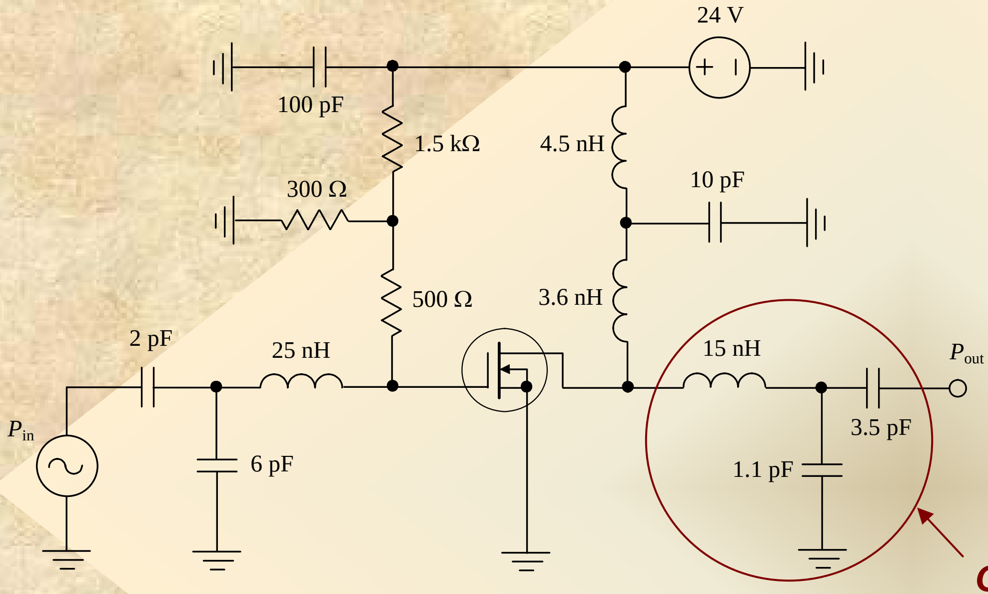
Normalized parameters:

$$m = \frac{R_L}{R_{out}} \qquad q = \frac{R_L}{Z_{03}\sqrt{3}}$$

$$n = \omega C_{out} Z_{02}$$

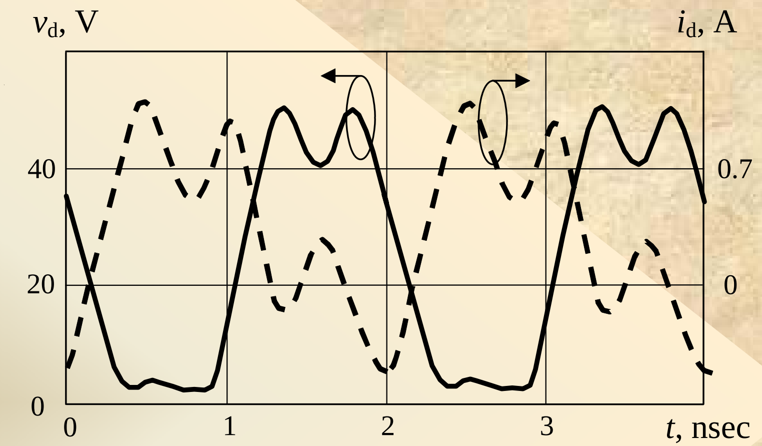
4. Class F: LDMOSFET power amplifier design example

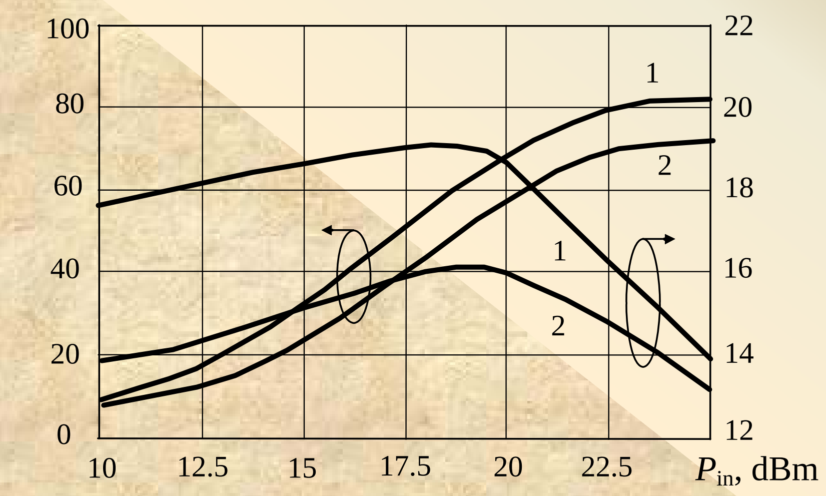
500 MHz Class F power amplifier with lumped elements



Output matching

Drain voltage and current waveforms



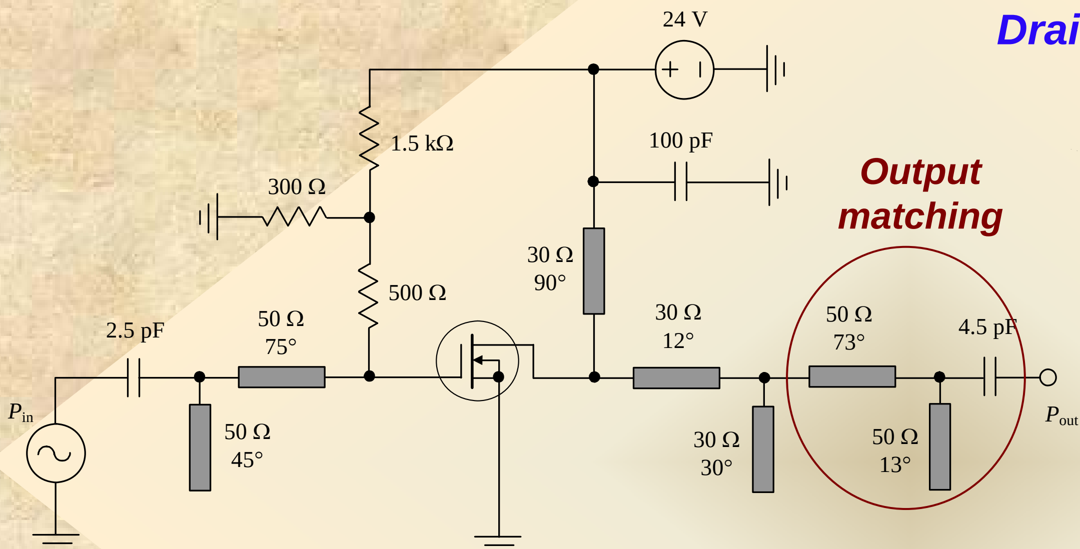


LDMOSFET:
gate length 1.25 um
gate width 7x1.44 mm

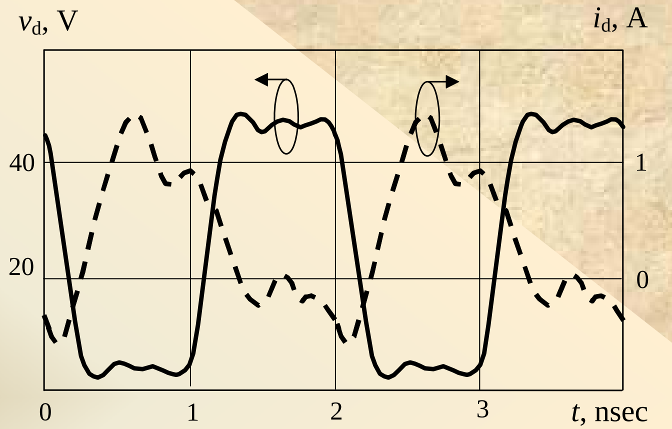
- ***inductance Q-factor = ∞***
  efficiency - 82%
  linear power gain > 16 dB
- ***inductance Q-factor = 30***
  efficiency - 71%
  linear power gain > 14 dB

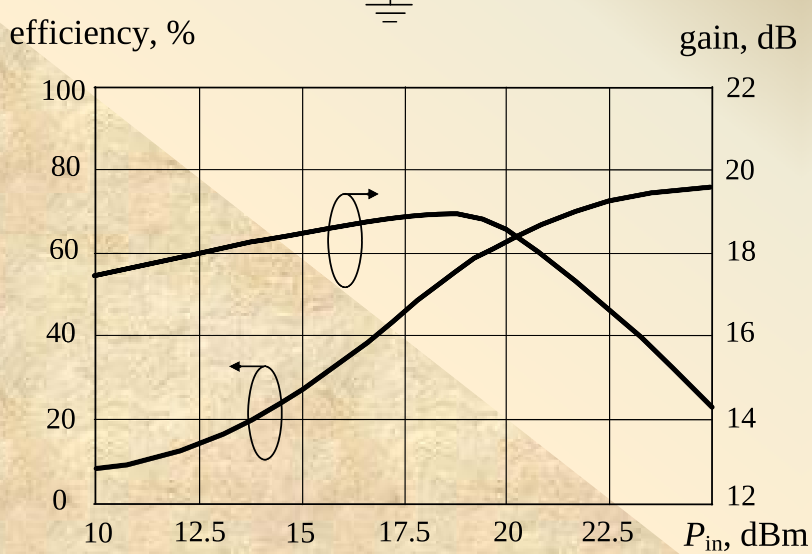
4. Class F: LDMOSFET power amplifier design example

500 MHz Class F power amplifier with transmission lines



Drain voltage and current waveforms





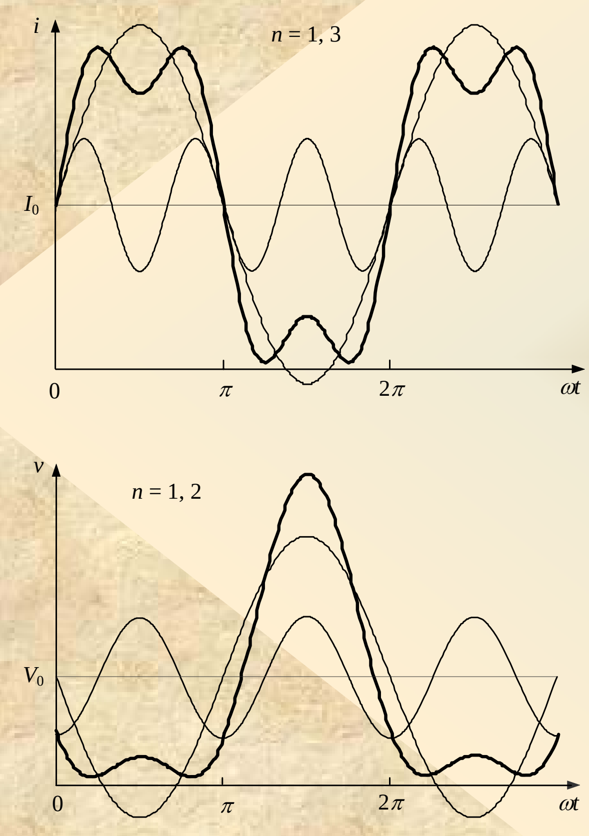
LDMOSFET:
gate length 1.25 um
gate width 7x1.44 mm

- ***T-matching circuit for output impedance transformation***
- ***output power - 39 dBm (8 W)***
- ***collector efficiency - 76%***
- ***linear power gain > 16 dB***

5. Inverse Class F: biharmonic and idealized operation modes

Second-harmonic peaking

Inverse voltage and current waveforms



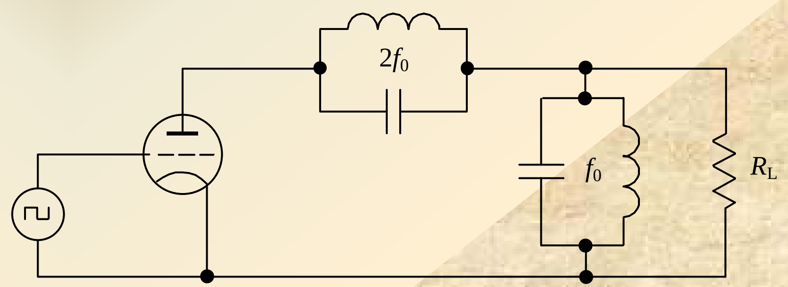
Fourier series for:

rectangular current waveform

$$\frac{i(\omega t)}{I_0} = 1 + \frac{4}{\pi}\sin\omega t + \frac{4}{3\pi}\sin 3\omega t + \frac{4}{\pi}\sum_{n=5,7,\ldots}^{N}\frac{\sin n\omega t}{n}$$

half-sinusoidal voltage waveform

$$\frac{v(\omega t)}{V_0} = 1 - \frac{\pi}{2}\sin\omega t - \frac{2}{3}\cos 2\omega t - 2\sum_{n=4,6,\ldots}^{N}\frac{\cos n\omega t}{n^2 - 1}$$

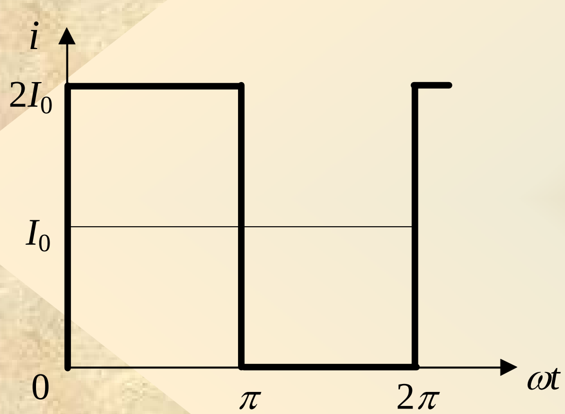


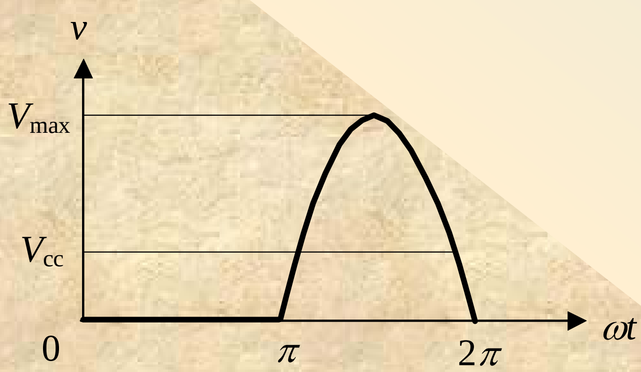
A. I. Kolesnikov, "A New Method to Improve Efficiency and to Increase Power of Transmitter (in Russian)," *Master Svyazi*, pp. 27-41, June 1940

5. Inverse Class F: idealized operation mode

Concept of inverse Class F mode was reintroduced for low voltage power amplifiers designed for monolithic applications (less collector current)

Dual to conventional Class F with mutually interchanged current and voltage waveforms





$$I_1 = \frac{4I_0}{\pi}$$ ***- fundamental current***

$$V_1 = \frac{V_{max}}{2} = \frac{\pi}{2} V_{cc}$$ ***- fundamental voltage***

$$P_1 = \frac{V_{max} I_0}{\pi}$$ ***- fundamental output power***

$$P_0 = V_{cc} I_0 = \frac{V_{max} I_0}{\pi}$$ ***- dc output power***

$$\eta = \frac{P_1}{P_0} = 100\%$$ ***- ideal collector/drain efficiency***

Harmonic impedance conditions:

$$Z_1 = R_1 = \frac{\pi}{8}\frac{V_{max}}{I_0} = \frac{\pi^2}{8}\frac{V_{cc}}{I_0}$$

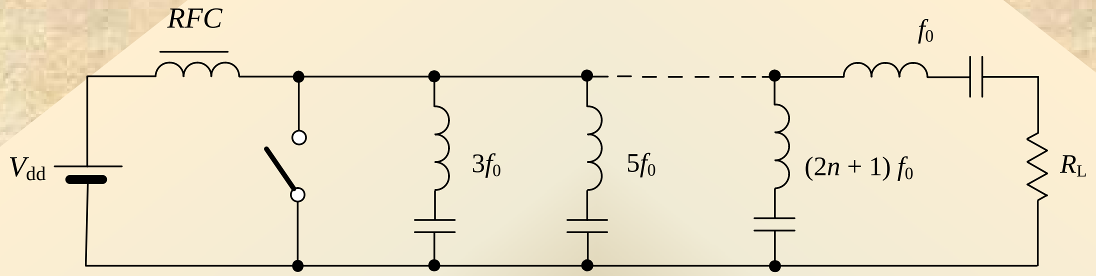
$$Z_n = 0 \qquad \text{for odd } n$$

$$Z_n = \infty \qquad \text{for even } n$$

5. Inverse Class F with quarterwave transmission line

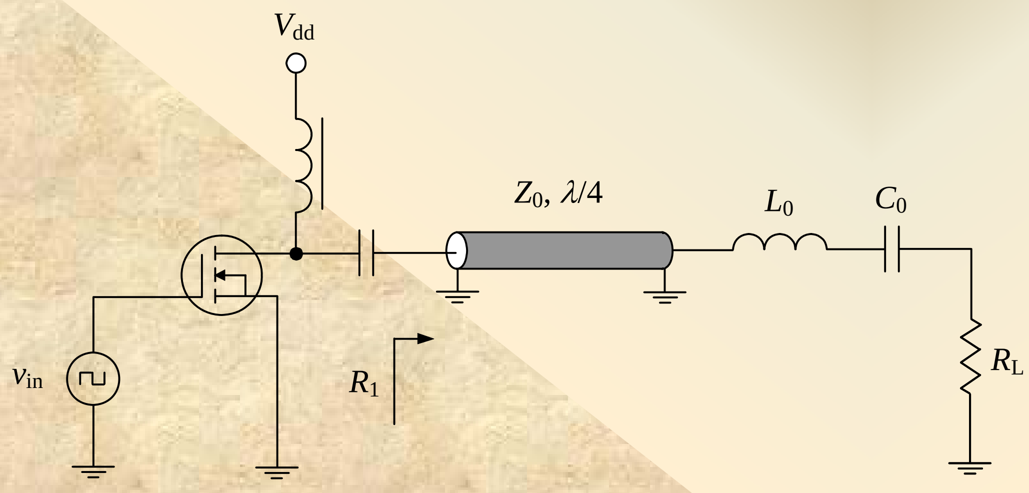
➢ ***device is driven to operate as switch***

➢ ***zero impedances at odd harmonic components***



➢ ***quarterwave transmission line as infinite set of series resonant circuits***

➢ ***sinusoidal current: shunt L_0C_0-circuit tuned to fundamental***

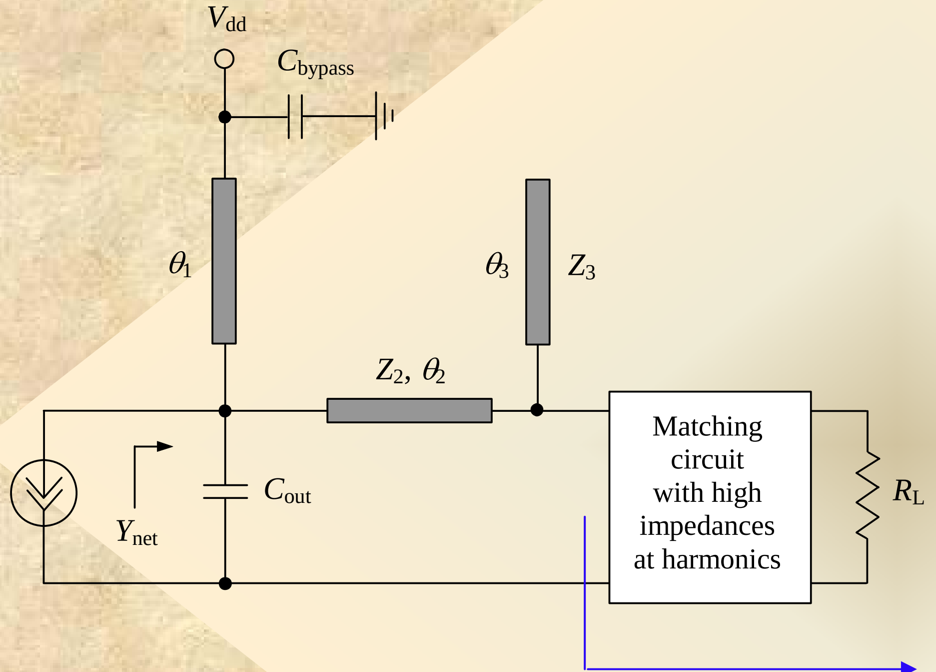


➢ ***quarterwave transmission line as impedance transformer***

$$R_1 = \frac{Z_0^2}{R_L}$$

6. Inverse Class F: second current and third voltage harmonic peaking

Load network



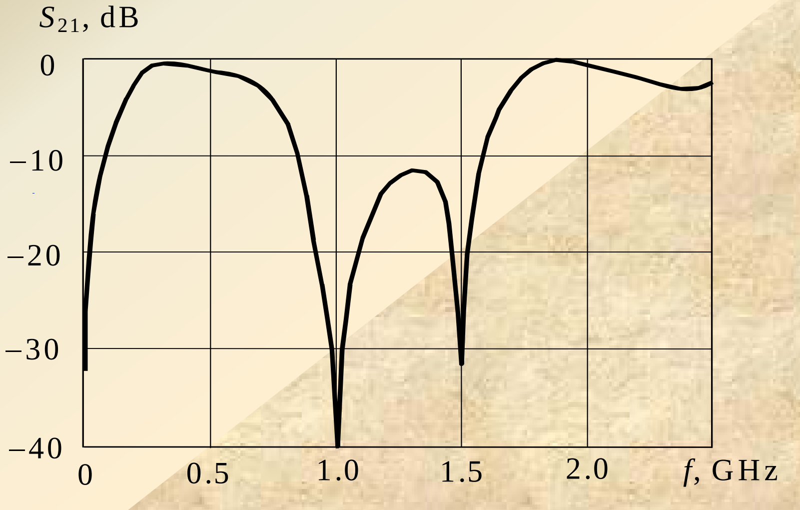
Harmonic impedance conditions at collector (drain):

$\mathrm{Im}Y_{net}(\omega_0) = 0$

$\mathrm{Im}Y_{net}(2\omega_0) = 0$

$\mathrm{Im}Y_{net}(3\omega_0) = \infty$

S_{21} simulation (f_0 = 500 MHz)



➢ *ideal transmission lines*

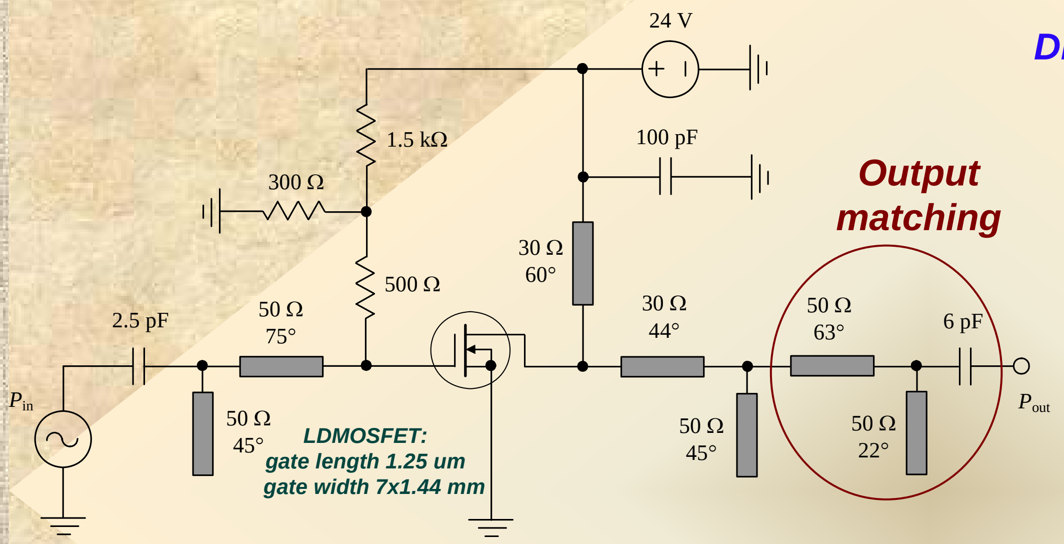
Circuit parameters:

$$\theta_1 = \frac{\pi}{3}, \qquad \theta_3 = \frac{\pi}{4}$$

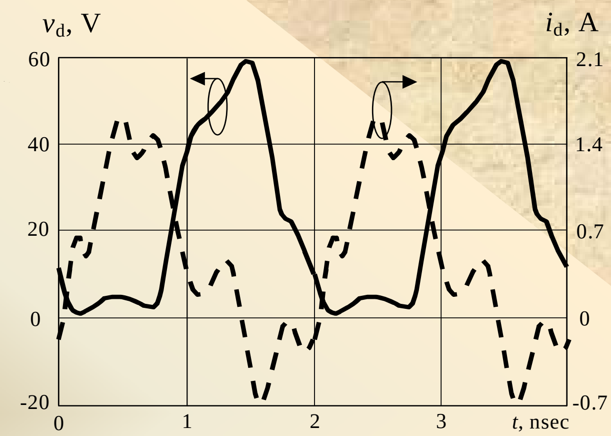
$$\theta_2 = \frac{1}{2}\tan^{-1}\left[\left(2Z_0\omega C_{out} + \frac{1}{\sqrt{3}}\right)^{-1}\right]$$

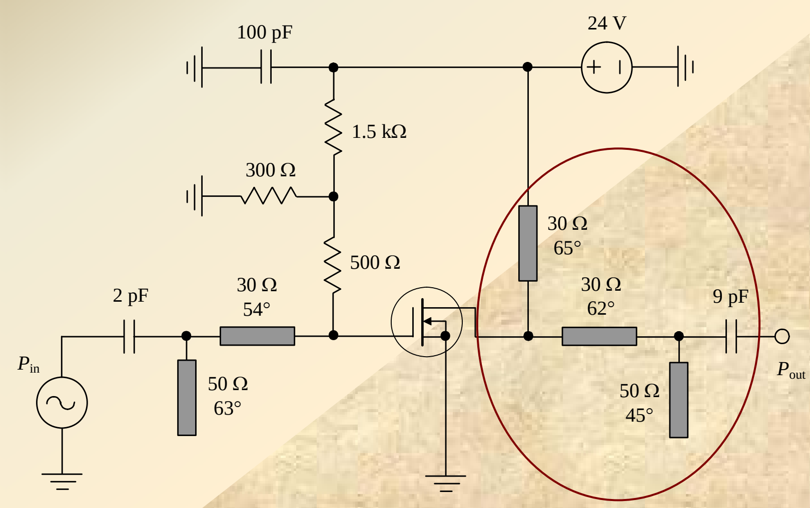
7. Inverse Class F: LDMOSFET power amplifier design example

500 MHz inverse Class F power amplifier with transmission lines



Drain voltage and current waveforms





- *output power - 39 dBm or 8 W*
- *collector efficiency - 71%*

Load network with output matching

Optimum load network resistances at fundamental for different classes of operation

Class B :

$$R^{(B)} = \frac{V_{cc}}{I_1} = \frac{V_{cc}^2}{2P_1}$$

Class F :

$$R^{(F)} = \frac{4}{\pi}\frac{V_{cc}}{I_1} = \frac{4}{\pi}R^{(B)}$$

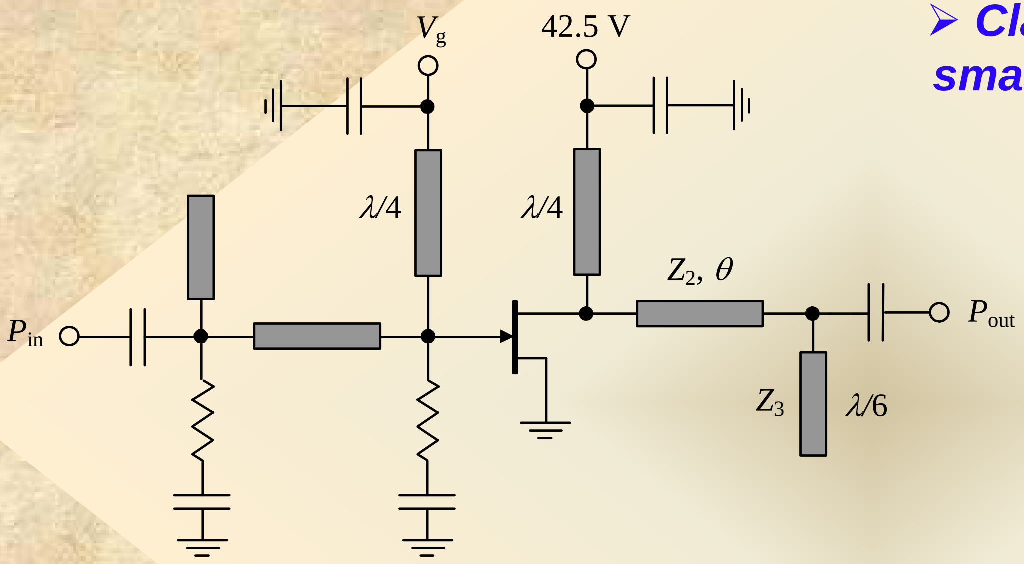
Inverse Class F :

$$R^{(invF)} = \frac{\pi}{2}\frac{V_{cc}}{I_1} = \frac{\pi^2}{8}R^{(F)} = \frac{\pi}{2}R^{(B)}$$

Load resistance in inverse Class F is the highest (1.6 times larger than in Class B) → ***Less impedance transformation ratio and easier matching procedure***

8. Practical high-efficiency RF and microwave Class F power amplifiers

Class F GaN HEMT power amplifier with input harmonic control



- ***Class AB biasing with small quiescent current***
- ***RC-circuits at the input for stable operation***
- ***characteristic impedance Z_2 and electrical length θ is tuned to form third-harmonic tank with output device capacitance C_{ds}***
- ***characteristic impedances Z_2 and Z_3 are chosen to provide conjugate impedance matching at fundamental***

Input second-harmonic termination circuit is used to provide input quasi-square voltage waveform minimizing device switching time

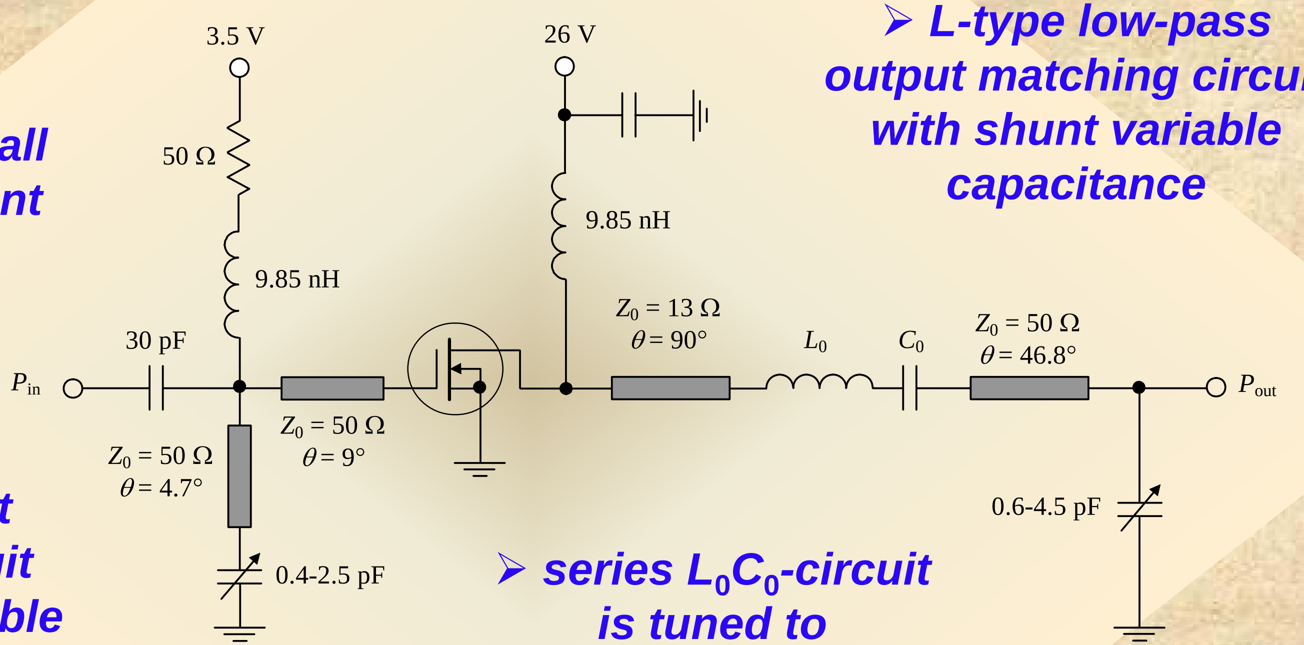
85% power-added efficiency for 16.5 W at 2 GHz

D. Schmelzer and S. I. Long, "A GaN HEMT Class F Amplifier at 2 GHz with > 80% PAE," *IEEE J. Solid-State Circuits*, vol. SC-42, pp. 2130-2136, Oct, 2007.

8. Practical high-efficiency RF and microwave Class F power amplifiers

Inverse Class F LDMOSFET power amplifier with quarterwave line

- ***Class AB biasing with small quiescent current***
- ***L-type low-pass output matching circuit with shunt variable capacitance***



- ***L-type input matching circuit with shunt variable capacitance***
- ***series L_0C_0-circuit is tuned to fundamental***

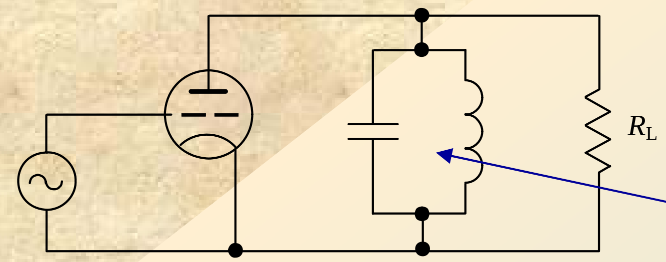
60% drain efficiency for 13 W at 1.78 GHz

F. Lepine, A. Adahl, and H. Zirath, "*L*-Band LDMOS Power Amplifiers Based on an Inverse Class-F Architecture," *IEEE Trans. Microwave Theory Tech*., vol. MTT-53, pp. 2007-2012, June 2005.

II. SWITCHED-MODE CLASS E POWER AMPLIFIERS

1. Effect of detuned resonant circuit
2. Basic Class E with shunt capacitance
3. Generalized Class E load network with finite dc-feed inductance
4. Parallel-circuit Class E
5. Class E approximation with transmission lines
6. Class E with quarterwave transmission line
7. Broadband Class E circuit design
8. Practical RF and microwave Class E power amplifiers

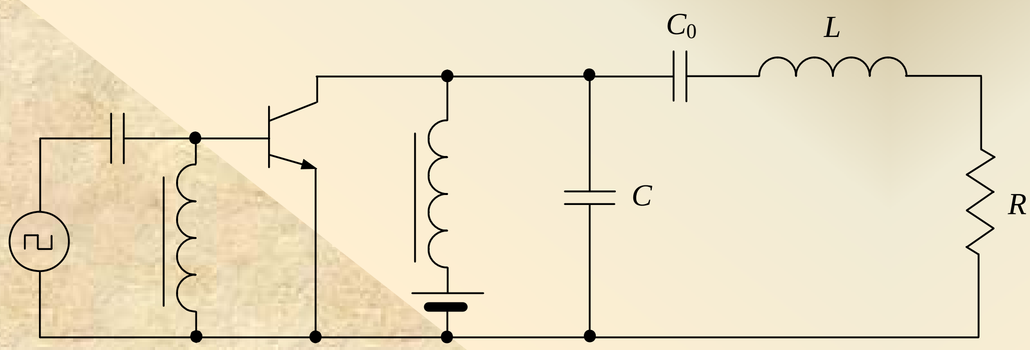
1. Effect of detuned resonant circuit



- ***anode efficiency of 92-93% for resonant-circuit phase angles of 30-40°: inductive impedance at fundamental and capacitive at harmonics***

resonant frequency $f \approx (1.4\text{-}1.5)f_0$
f_0 – fundamental frequency

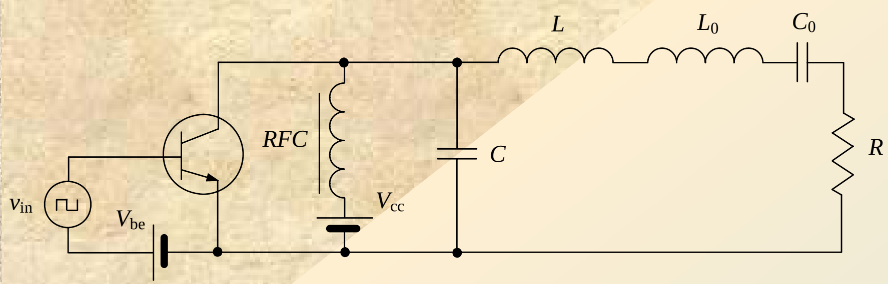
E. P. Khmelnitsky, *Operation of Vacuum-Tube Generator on Detuned Resonant Circuit* (in Russian), Moskva: Svyazizdat, 1962.

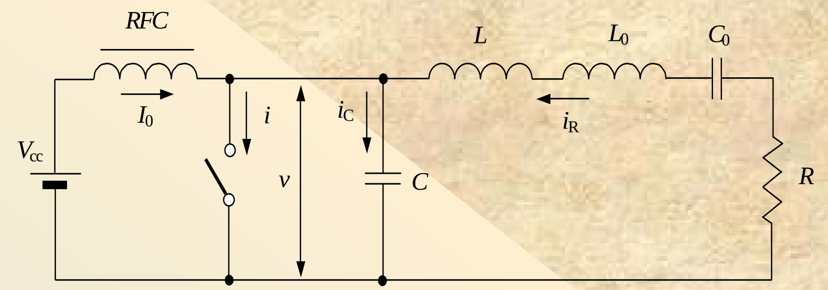


- ***load current lags collector voltage so that series LC_0-circuit must appear inductive at operating frequency***
- ***pulsed excitation with highest efficiency for conduction angles less than 180°***
- ***collector efficiency of 94% for 20 W 500 kHz bipolar power amplifier with 50% duty cycle***

G. D. Ewing, *High-Efficiency Radio-Frequency Power Amplifiers*, Ph.D. Dissertation, Oregon State University, June 1964.

2. Basic Class E with shunt capacitance





Idealized assumptions for analysis:

- ***transistor has zero saturation voltage, zero on-resistance, infinite off-resistance and its switching action is instantaneous and lossless***
- ***RF choke allows only dc current and has no resistance***
- ***total shunt capacitance is assumed to be linear***
- ***reactive elements in load network are lossless***
- ***loaded quality factor Q_L of series fundamentally tuned resonant L_0C_0 -circuit is infinite to provide pure sinusoidal current flowing into load***
- ***for optimum operation 50% duty cycle is used***

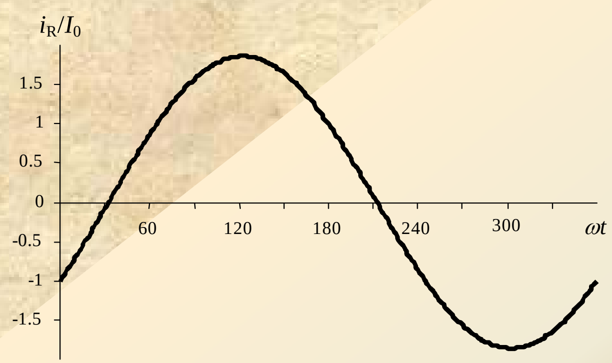
Idealized optimum or nominal conditions

$$v(\omega t)\Big|_{\omega t=2\pi} = 0$$

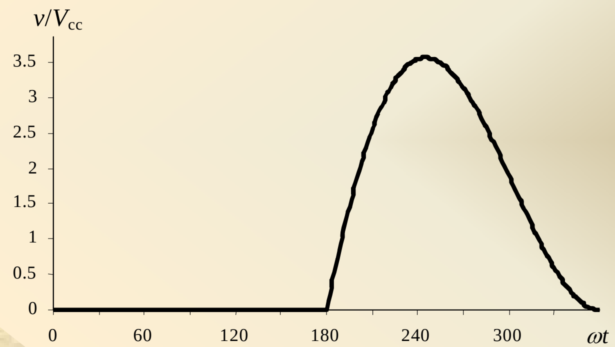
$$\frac{dv(\omega t)}{d\omega t}\bigg|_{\omega t=2\pi} = 0$$

2. Basic Class E with shunt capacitance

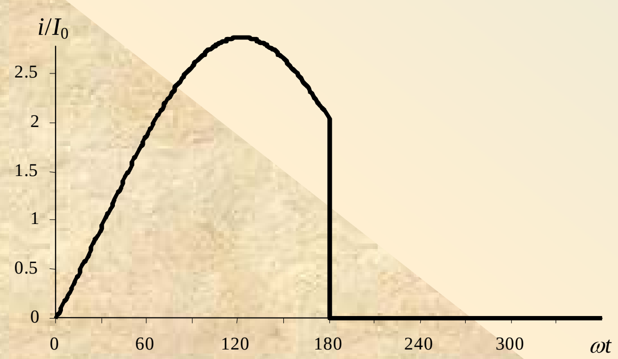
Load current



Collector voltage



Collector current



Optimum circuit parameters :

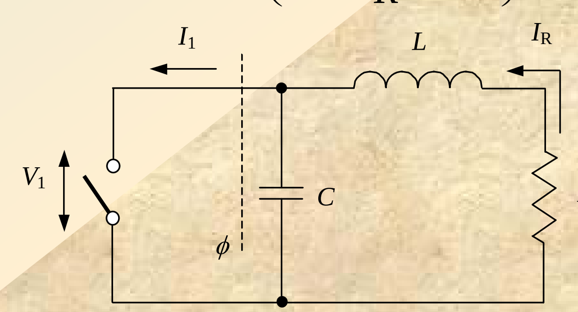
$$L = 1.1525\frac{R}{\omega}$$ - series inductance

$$C = 0.1836\frac{1}{\omega R}$$ - shunt capacitance

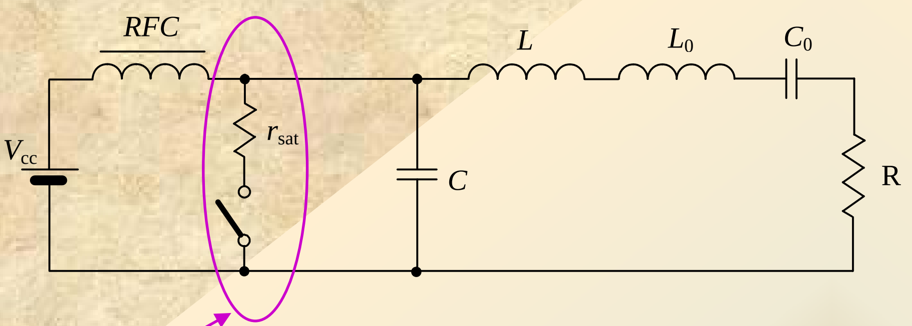
$$R = 0.5768\frac{V_{cc}^2}{P_{out}}$$ - load resistance

Optimum phase angle at fundamental seen by switch :

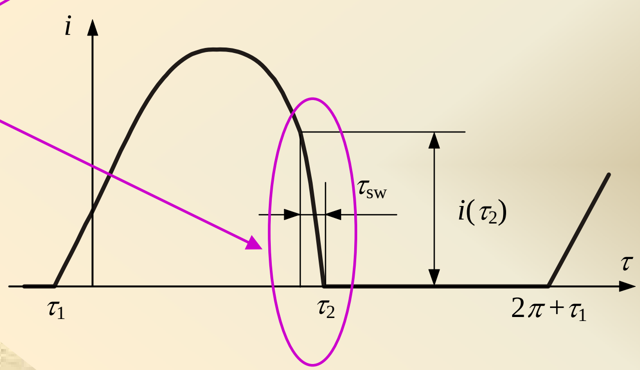
$$\phi = \tan^{-1}\left(\frac{\omega L}{R}\right) - \tan^{-1}\left(\frac{\omega CR}{1 - \frac{\omega L}{R}\omega CR}\right) = 35.945^{\circ}$$

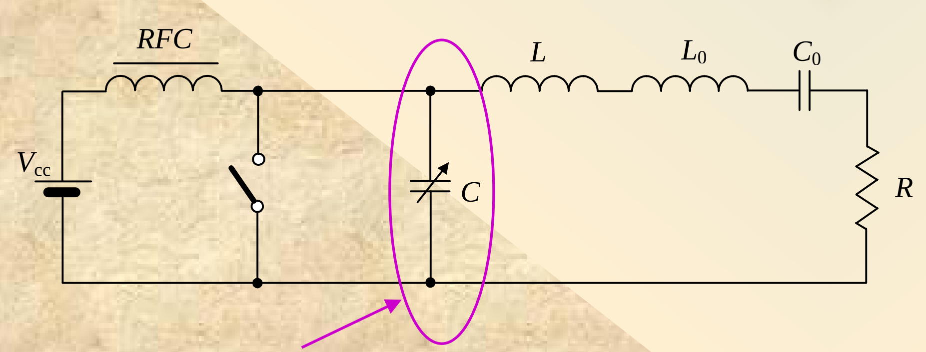


2. Basic Class E with shunt capacitance



Non-ideal switch





Nonlinear capacitance

Power loss due to non-zero saturation resistance

$$\frac{P_{sat}}{P_{dc}} \cong \frac{8}{3}\frac{r_{sat}P_{out}^2}{V_{cc}^2} \cong 1.365\frac{r_{sat}}{R}$$

Power loss due to finite switching time

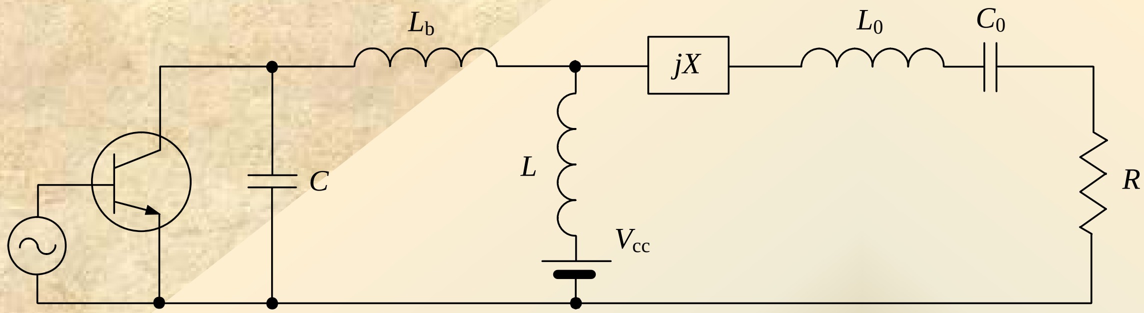
$$\frac{P_{sw}}{P_{dc}} \cong \frac{\tau_{sw}^2}{12}$$

For $\tau_{sw} = 0.35 \text{ or } 20^\circ$

only 1% efficiency loss

For nonlinear capacitances represented by abrupt junction collector capacitance with γ ***= 0.5, peak collector voltage increases by 20%***

3. Generalized Class E load network with finite dc-feed inductance



Optimum ideal voltage conditions across switch:

$$v(\omega t)\big|_{\omega t = 2\pi} = 0$$

$$\left.\frac{dv(\omega t)}{d\omega t}\right|_{\omega t = 2\pi} = 0$$

$$i_R(\omega t) = I_R \sin(\omega t + \varphi)$$ - *sinusoidal current in load*

- *load network consists of dc-feed inductance L supplying also dc current, shunt capacitor C, series reactance X, bondwire inductance L_b, series fundamentally tuned L_0C_0 resonant circuit, and load R*
- *shunt capacitor C can represent intrinsic device output capacitance and external circuit capacitance*
- *active device is considered as ideal switch to provide instantaneous device switching between its on-state and off-state operation conditions*
- *series reactance X can be positive (inductance), zero and negative (capacitive)*

3. Generalized Class E load network with finite dc-feed inductance

$$\omega^2 (L + L_b) LC \frac{d^2 v(\omega t)}{d(\omega t)^2} + v(\omega t) - V_{cc} - \omega L I_R \cos(\omega t + \varphi) = 0$$

- second-order differential equation

$$\frac{v(\omega t)}{V_{cc}} = C_1 \cos(q\omega t) + C_2 \sin(q\omega t) + 1 - \frac{q^2 p}{1 - q^2} \cos(\omega t + \varphi)$$

where $q = 1/\omega\sqrt{(L + L_b)C}, \qquad p = \dfrac{\omega L I_R}{V_{cc}},$

and coefficients C_1 and C_2 are defined from initial conditions

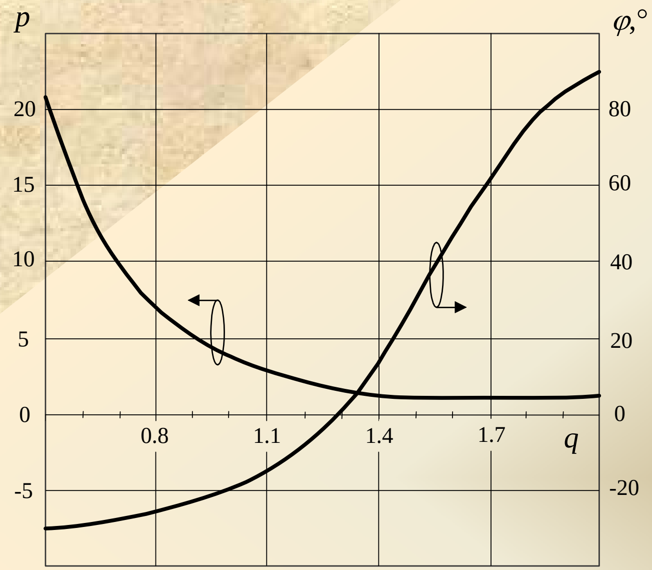
$$\omega CR = 1/q^2 \left(1 + \frac{L_b}{L}\right) \frac{\omega L}{R}$$ ***- shunt capacitance***

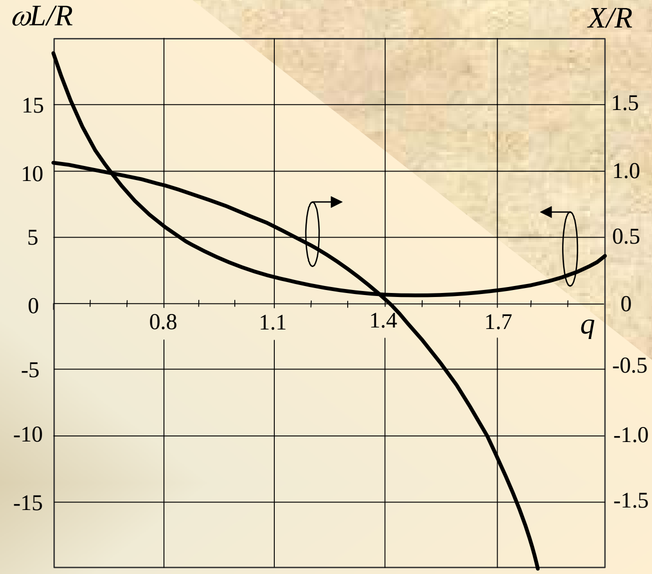
$$\frac{\omega L}{R} = p\left(1 + \frac{L_b}{L}\right) / \left(\frac{\pi}{2p} + \frac{2}{\pi}\cos\varphi - \sin\varphi\right)$$ ***- dc-feed inductance***

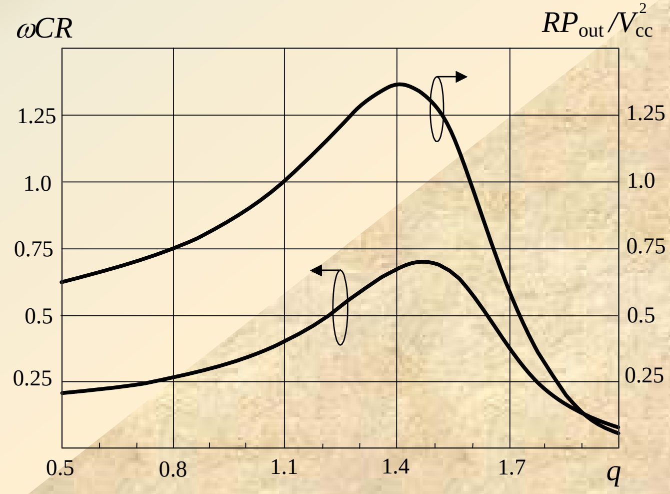
$$R = \frac{1}{2\pi^2}\left(\frac{\pi^2}{2p} + 2\cos\varphi - \pi\sin\varphi\right)^2 \frac{V_{cc}^2}{P_{out}} / \left(1 + \frac{L_b}{L}\right)^2$$ ***- load resistance***

3. Generalized Class E load network with finite dc-feed inductance

Normalized load network parameters versus $q = 1/\omega\sqrt{LC}$, $L_b = 0$

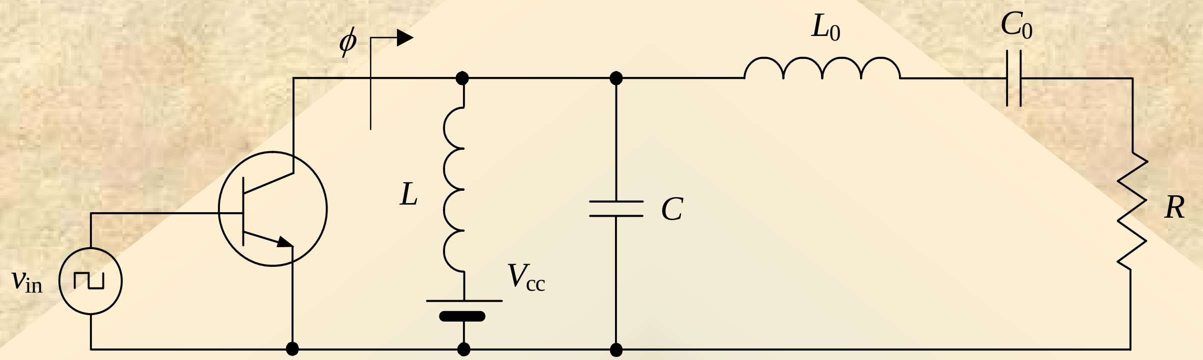






- ***q*** **≤ 0.5: close to Class E with shunt capacitance with positive (inductive) series reactance (*X* > 0)**
- ***q*** **= 1.412: parallel-circuit Class E with zero reactance (*X* = 0) – maximum load resistance *R***
- ***q*** **= 1.468: maximum shunt capacitance *C* (maximum operating frequency f_{max}) with negative (capacitive) reactance (X < 0)**

4. Parallel-circuit Class E



To define three unknown parameters q, φ and p, two ideal optimum conditions and third equation for zero reactive part of fundamental Fourier component are applied resulting to system of three algebraic equations:

$$v(\omega t)\Big|_{\omega t=2\pi} = 0 \qquad \frac{dv(\omega t)}{d\omega t}\Bigg|_{\omega t=2\pi} = 0$$

$$V_X = -\frac{1}{\pi}\int_0^{2\pi} v(\omega t)\cos(\omega t+\varphi)\,d(\omega t) = 0$$

$$q = 1.412 \qquad p = 1.210$$

$$\varphi = 15.155^\circ$$

Optimum circuit parameters :

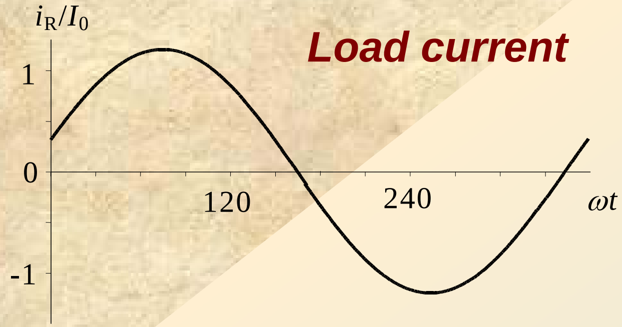
$$L = 0.732\frac{R}{\omega}$$ ***- parallel inductance***

$$C = \frac{0.685}{\omega R}$$ ***- parallel capacitance***

$$R = 1.365\frac{V_{cc}^2}{P_{out}}$$ ***- load resistance: highest value in Class E***

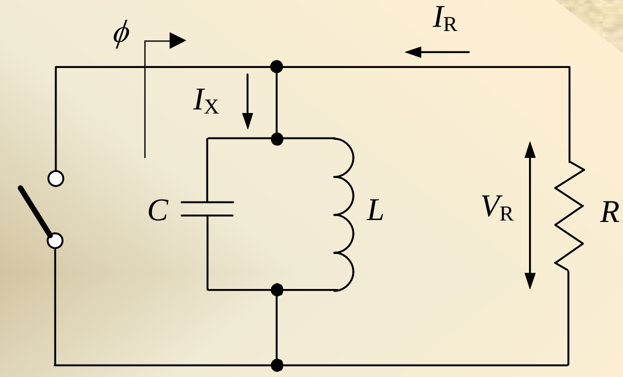
4. Parallel-circuit Class E

Load current

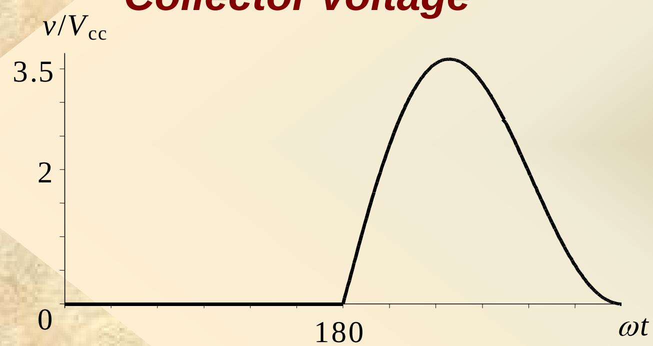


Inductive impedance at fundamental

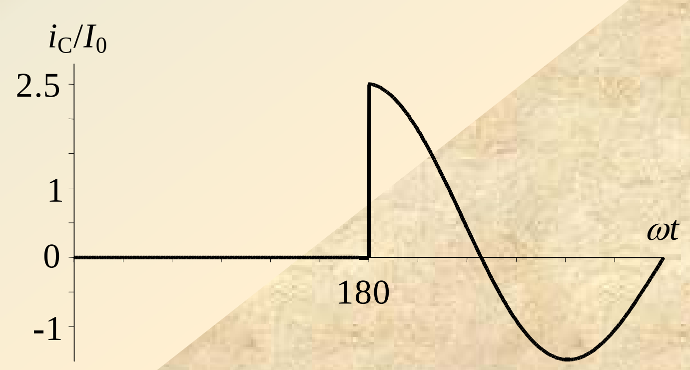
$$\phi = \tan^{-1}\left(\frac{I_X}{I_R}\right) = \tan^{-1}\left(\frac{R}{\omega L} - \omega RC\right) = 34.244°$$



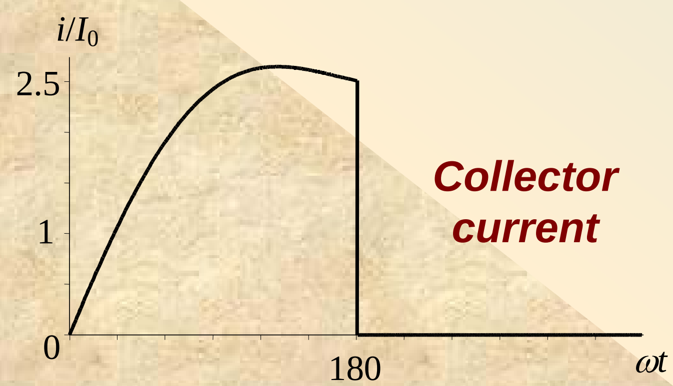
Collector voltage



Current through capacitance

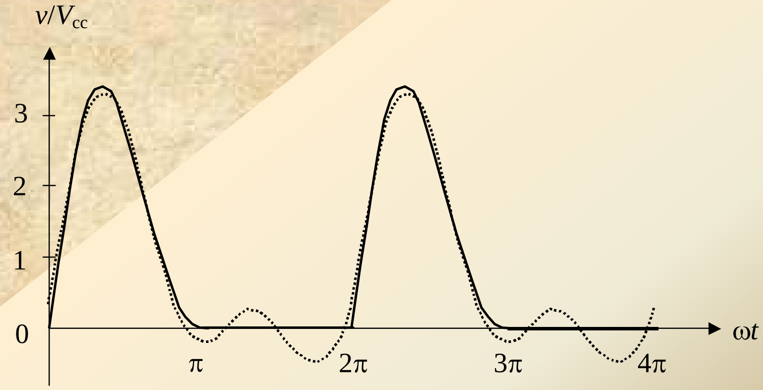


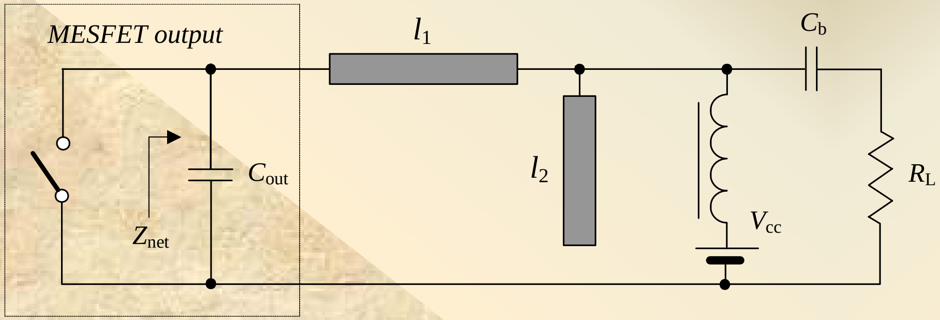
Collector current



5. Class E with transmission lines: approximation

Two-harmonic collector voltage approximation





Optimum impedance at fundamental seen by device :

$$Z_{\mathrm{net1}} = R\left(1 + j\tan 49.052^{\circ}\right)$$

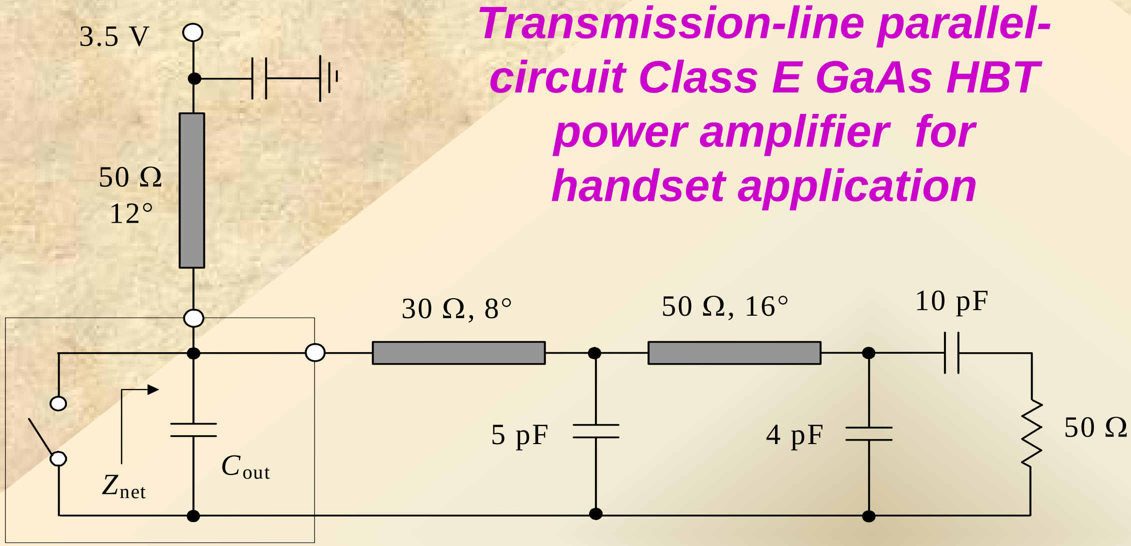
- ***electrical lengths of transmission lines l_1 and l_2 should be of 45° to provide open circuit seen by device at second harmonic***

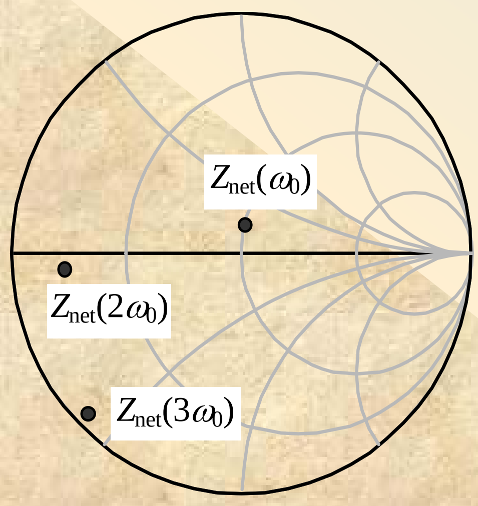
- ***transmission-line characteristic impedances are chosen to provide optimum inductive impedance seen by device output at fundamental***

T. B. Mader and Z. B. Popovic, “The Transmission-Line High-Efficiency Class-E Amplifier,” *IEEE Microwave and Guided Wave Lett*., vol. 5, pp. 290-292, Sept. 1995

5. Class E with transmission lines: approximation

Transmission-line parallel-circuit Class E GaAs HBT power amplifier for handset application

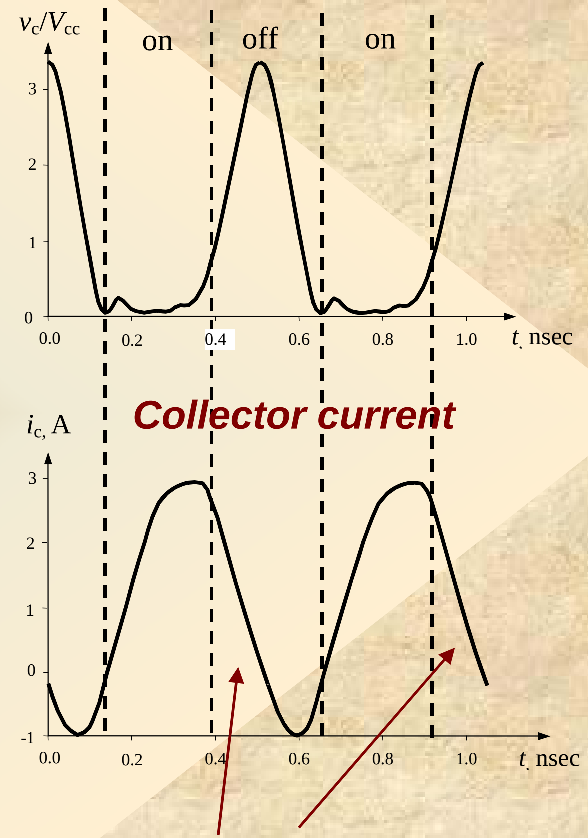




- ***parameters of parallel transmission line is chosen to realize optimum inductive impedance at fundamental***

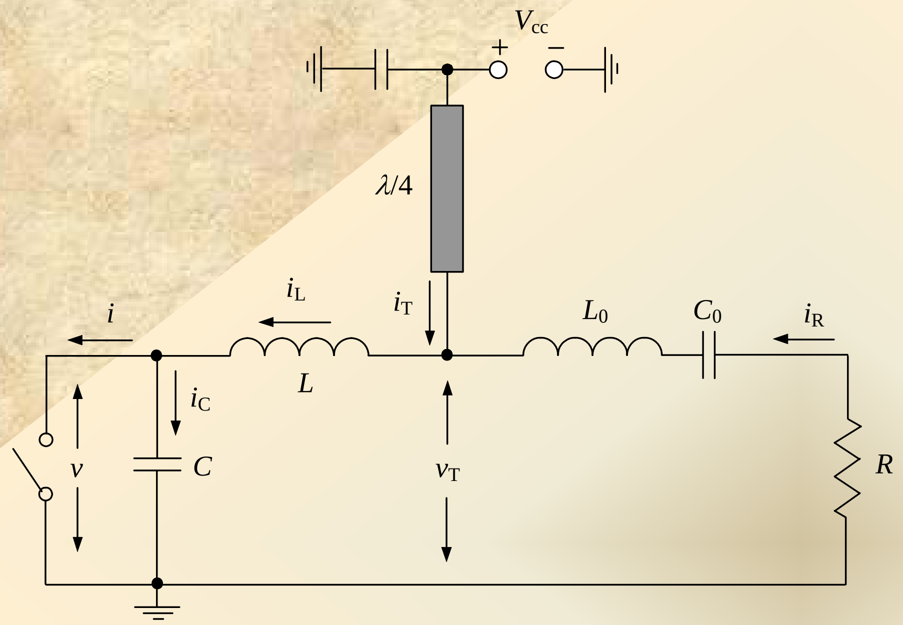
- ***output matching circuit consisting of series microstrip line with two shunt capacitors should provide capacitive reactances at second and third harmonics***

Collector voltage



Current flowing through collector capacitor

6. Class E with quarterwave transmission line



Optimum voltage conditions across switch:

$$v(\omega t)\big|_{\omega t=2\pi} = 0$$

$$\left.\frac{dv(\omega t)}{d\omega t}\right|_{\omega t=2\pi} = 0$$

- **sinusoidal load current**
- **50% duty cycle**

$$\frac{d^2 i_C(\omega t)}{d(\omega t)^2} + \frac{q^2}{2} i_C(\omega t) + I_R \sin(\omega t + \varphi) = 0$$

- second-order differential equation

Boundary conditions:

$$i_C(\omega t)\big|_{\omega t=\pi} = 2 i_R(\pi)$$

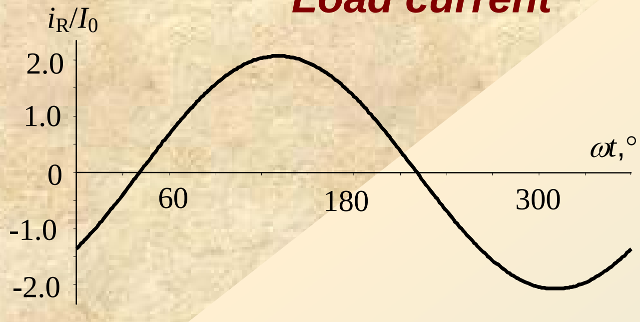
$$\left.\frac{d i_C(\omega t)}{d(\omega t)}\right|_{\omega t=\pi} = \frac{V_{cc}}{\omega L} - I_R \cos(\varphi)$$

$$p = \frac{\omega L I_R}{V_{cc}} \qquad q = 1/\omega\sqrt{LC}$$

$$q = 1.649 \quad p = 1.302 \quad \varphi = -40.8°$$

6. Class E with quarterwave transmission line

Load current



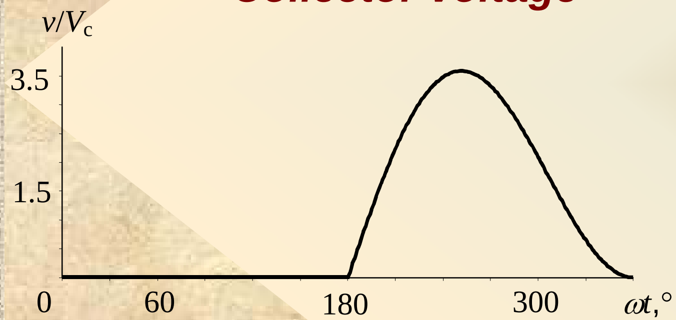
Optimum circuit parameters :

$$L = 1.349\frac{R}{\omega}$$ - series inductance

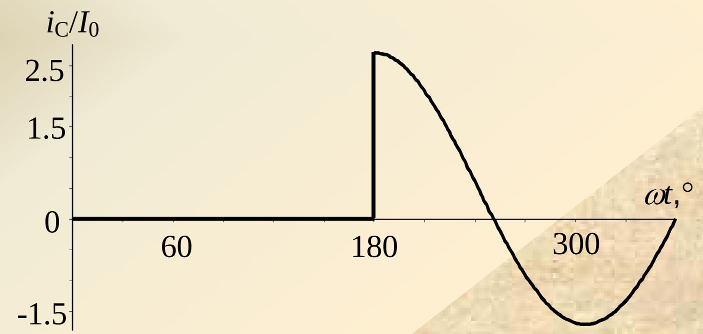
$$C = \frac{0.2725}{\omega R}$$ - shunt capacitance

$$R = 0.465\frac{V_{cc}^2}{P_{out}}$$ - load resistance

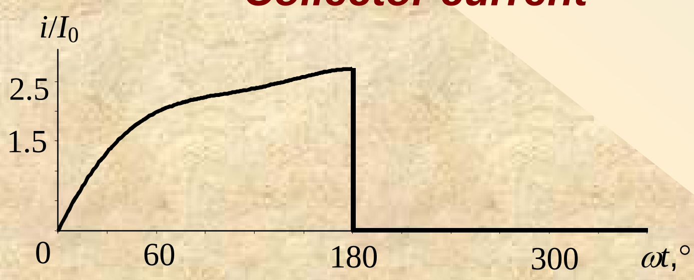
Collector voltage



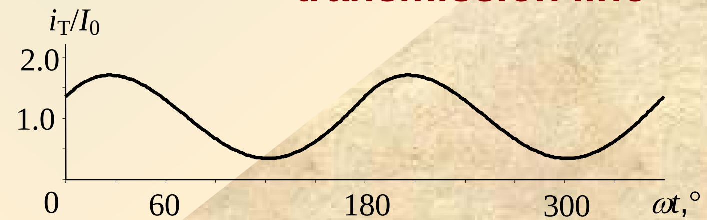
Current through capacitance



Collector current

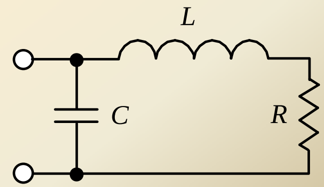
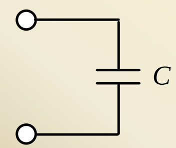
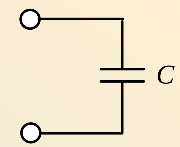
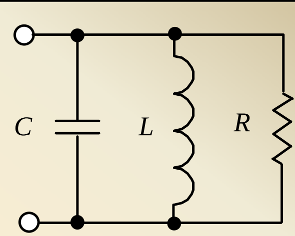
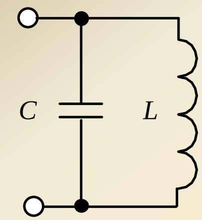
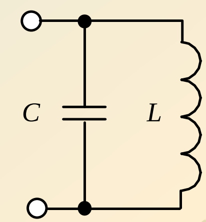
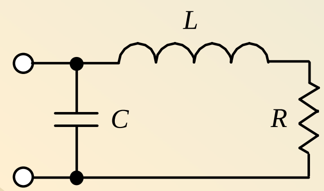
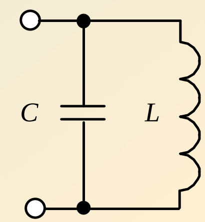
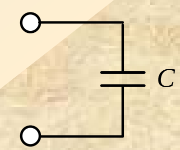


Current through transmission line



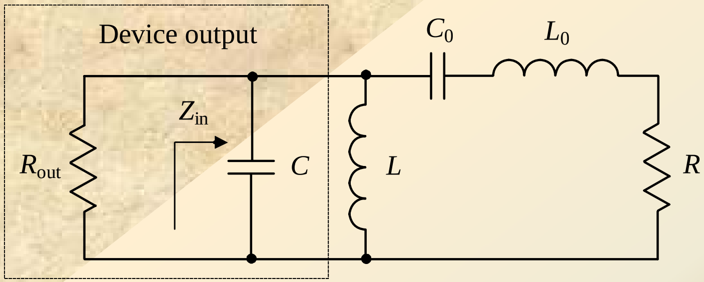
6. Class E with quarterwave transmission line

Optimum impedances at fundamental and harmonics for different Class E load networks

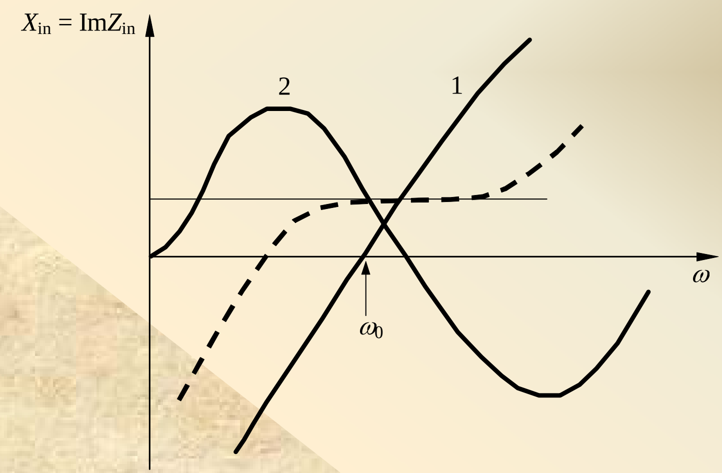
Class E load network	f_0 (fundamental)	$2nf_0$ (even harmonics)	$(2n+1)f_0$ (odd harmonics)
Class E with shunt capacitance			
Class E with parallel circuit			
Class E with quarterwave transmission line			

7. Broadband Class E circuit design

Reactance compensation load network



Reactance compensation principle



1 - impedance provided by series L_0C_0 resonant circuit

2 - impedance provided by parallel LC resonant circuit

- ***summation of reactances with opposite slopes results in constant load phase over broad frequency range***

Input load network admittance

$$Y_{in} = \left(j\omega C + \frac{1}{j\omega L} + \frac{1}{R + j\omega' L_0} \right)$$

$$\omega' = \omega \left(1 - \frac{\omega_0^2}{\omega^2} \right) \qquad \omega_0 = 1/\sqrt{L_0 C_0}$$

To maximize bandwidth:

$$\left. \frac{d\,\mathrm{Im}\,Y_{in}(\omega)}{d\omega} \right|_{\omega=\omega_0} = 0$$

$$C + \frac{1}{\omega^2 L} - \frac{2L_0}{R^2} = 0$$

Optimum parameters for series resonant circuit in Class E mode

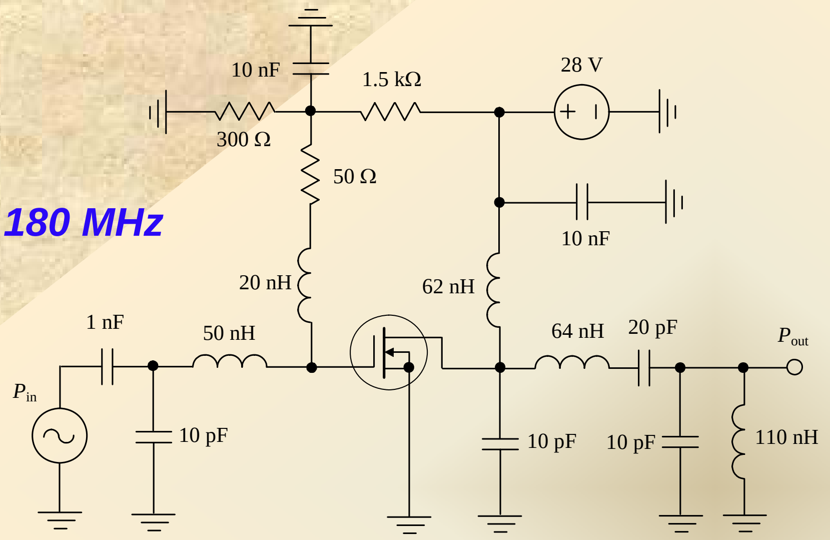
$$L_0 = 1.026\,\frac{R}{\omega}$$

$$C_0 = 1/\omega^2 L_0$$

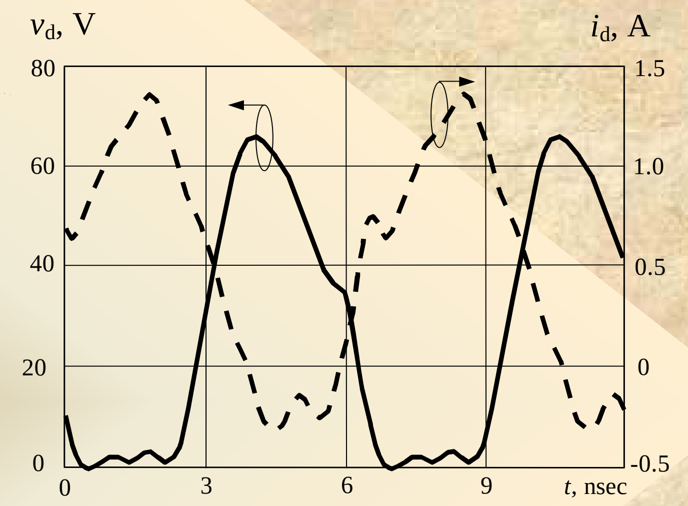
7. Broadband Class E circuit design

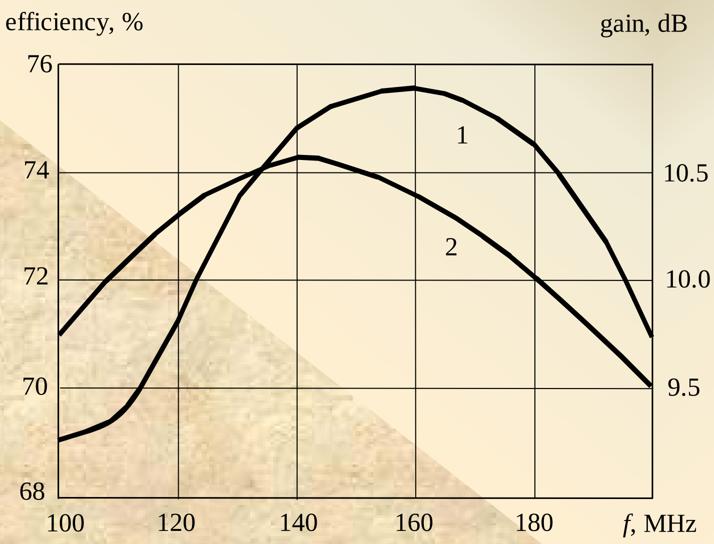
Broadband Class E power amplifier with reactance compensation

f_0 = 120…180 MHz



Drain voltage and current waveforms





LDMOSFET:
gate length 1.25 um
gate width 7x1.44 mm

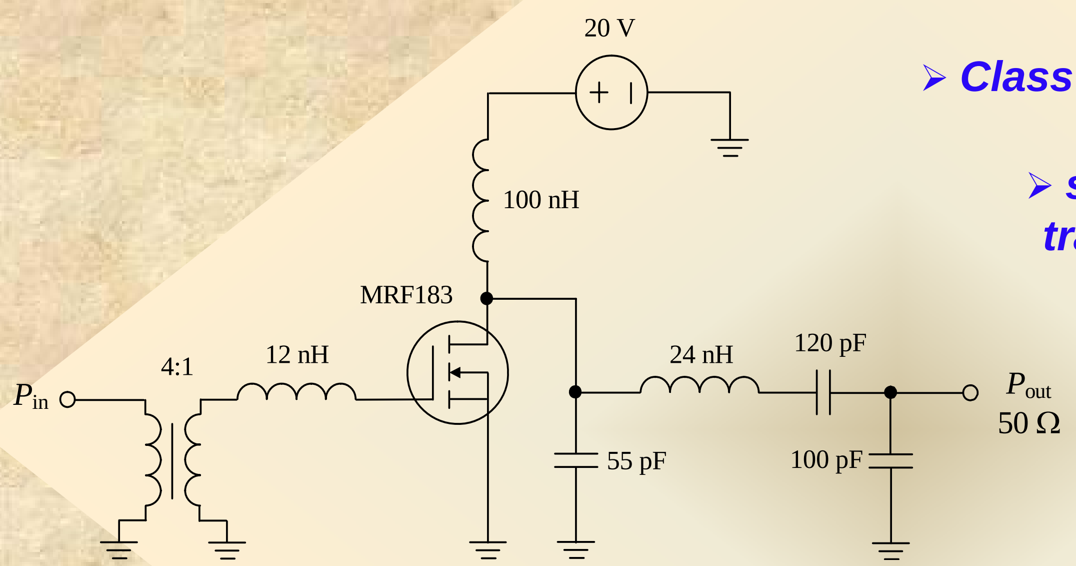
1 - drain efficiency > 71%

2 - power gain > 9.5 dB

- input power - 1 W
- input VSWR < 1.4
- gain flatness ≤ ± 0.3

8. Practical RF and microwave Class E power amplifiers

High power LDMOSFET RF Class E power amplifier



- ***Class B with zero quiescent current***
- ***series inductance and ferrite 4:1 transformer is required to match device input impedance***
- ***L-type output transformer to match optimum 1.5 Ω output impedance to 50 Ω load***
- ***quality factor of resonant circuit was chosen to be sufficiently low (~5) to provide some frequency bandwidth operation and to reduce sensitivity to resonant circuit parameters***
- ***required value of Class E shunt capacitance is provided by device intrinsic 38 pF capacitance and external 55 pF capacitance***

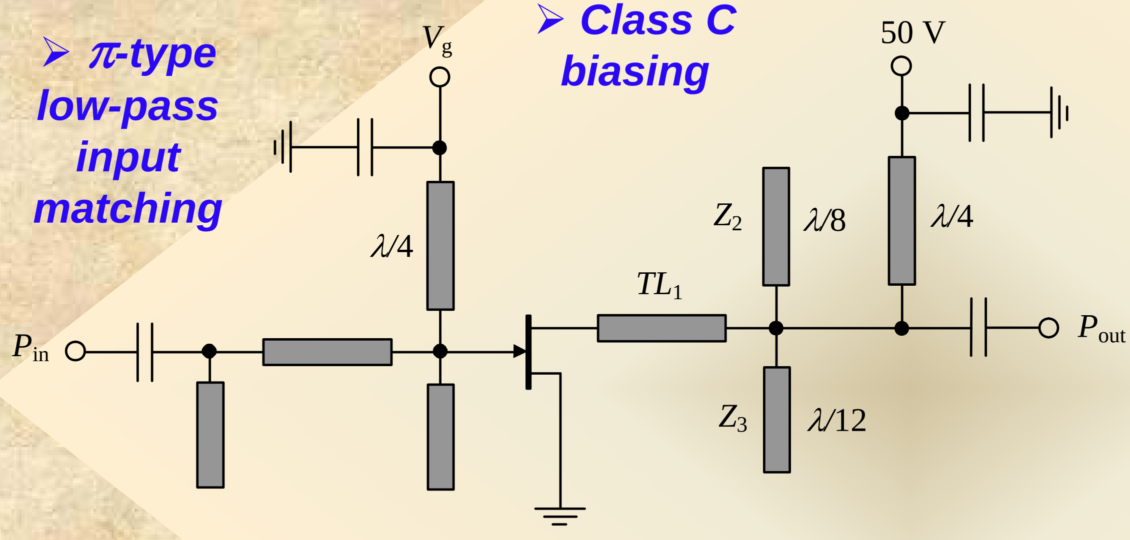
70% drain efficiency for 54 W at 144 MHz

H. Zirath and D. B. Rutledge, "An LDMOS VHF Class-E Power Amplifier Using a High-*Q* Novel Variable Inductor," *IEEE Trans. Microwave Theory Techn.*, vol. 47, pp. 359-362, Dec. 1999.

8. Practical RF and microwave Class E power amplifiers

Transmission-line low-harmonic GaN HEMT Class E power amplifier

- ***π*-type low-pass input matching**
- ***Class C biasing***



- ***short transmission line TL_1 provides required series inductive reactance***
- ***output open-circuit stubs are tuned to be quarterwave at 2nd and 3rd harmonics and capacitive at fundamental***
- ***characteristic impedances Z_2 and Z_3 are chosen to provide load matching together with series line TL_1***

Input second-harmonic termination circuit is used to provide input quasi-square voltage waveform minimizing device switching time

74% power-added efficiency for 11.4 W at 2 GHz

H. G. Bae, R. Negra, S. Boumaiza, and F. M. Ghannouchi, "High-Efficiency GaN Classs-E Power Amplifier with Compact Harmonic-Suppression Network," Proc. 37th European Microwave Conf., pp. 1093-1096, 2007.

III. SWITCHED-MODE CLASS FE POWER AMPLIFIERS

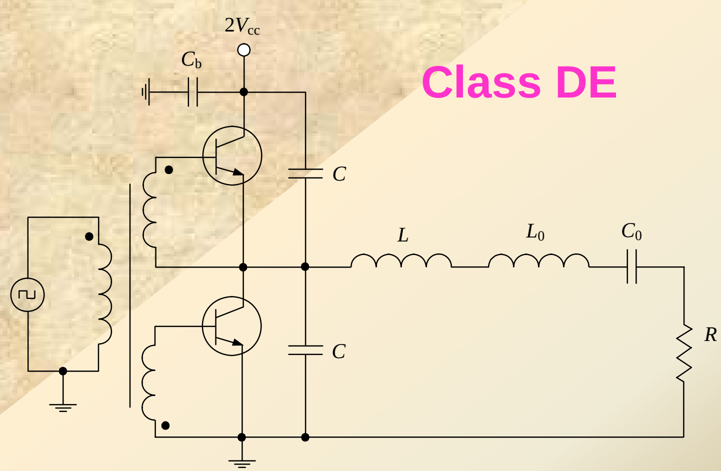
1. Basic load network and operation principle

2. Load network parameters and voltage and current waveforms

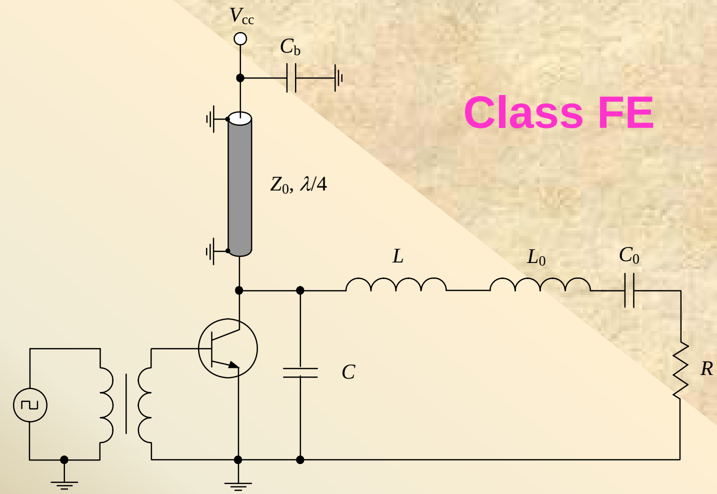
3. Design approximations with second-harmonic control (Class EF_2) and third-harmonic control (Class E/F_3)

1. Basic load network and operation principle

Class DE



Class FE



- ***Class E idealized optimum conditions applied to Class F mode affected by shunt parasitic capacitance, with added series inductance***
- ***symmetrizing action of shunt quarterwave line provides its voltage inverter mode resulting in similar waveform as in Class D or Class DE: it stores voltage waveform in traveling wave along its length which returns delayed by one-half fundamental period and inverted due to reflection from short-circuited end***

Idealized optimum conditions

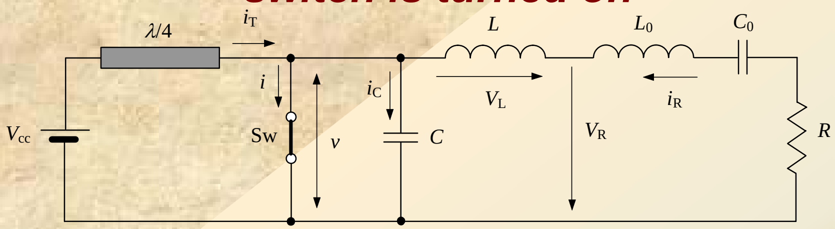
$$v(\omega t)\big|_{\omega t=2\pi} = 0$$

$$\left.\frac{dv(\omega t)}{d\omega t}\right|_{\omega t=2\pi} = 0$$

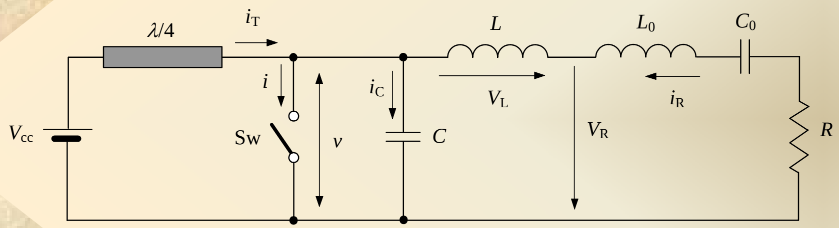
- ***transistor has zero saturation voltage, zero on-resistance, infinite off-resistance and its switching action is instantaneous and lossless***

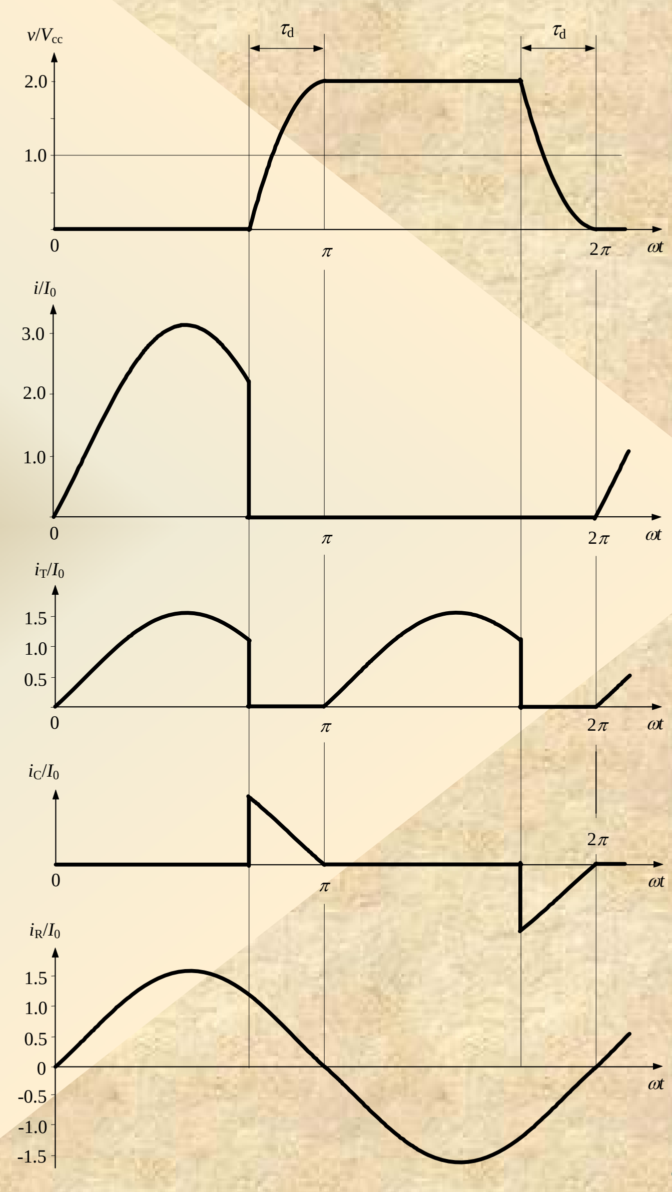
1. Basic load network and operation principle

switch is turned on



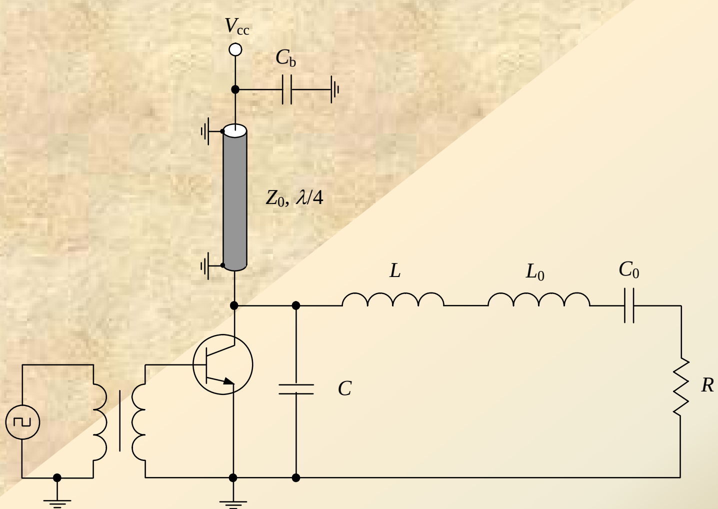
switch is turned off





- ***dead time during charging or discharging process when current flow through shunt capacitance***
- ***half-wave symmetry of transmission-line current waveform: line attempts to do same work in first and second halves of cycle***
- ***zero initial phase and duty cycle D < 0.5***

2. Load network parameters and voltage and current waveforms



τ_d - dead time

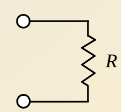
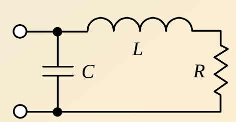
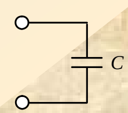
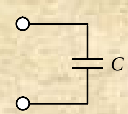
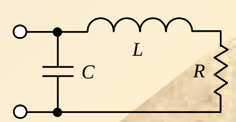
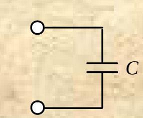
Optimum circuit parameters :

$$R = \frac{2\left(1+\cos\tau_d\right)^2}{\pi^2}\frac{V_{cc}^2}{P_{out}}$$ - load resistance

$$L = \frac{\tau_d - \sin\tau_d\cos\tau_d}{\sin^2\tau_d}\frac{R}{\omega}$$ - series inductance

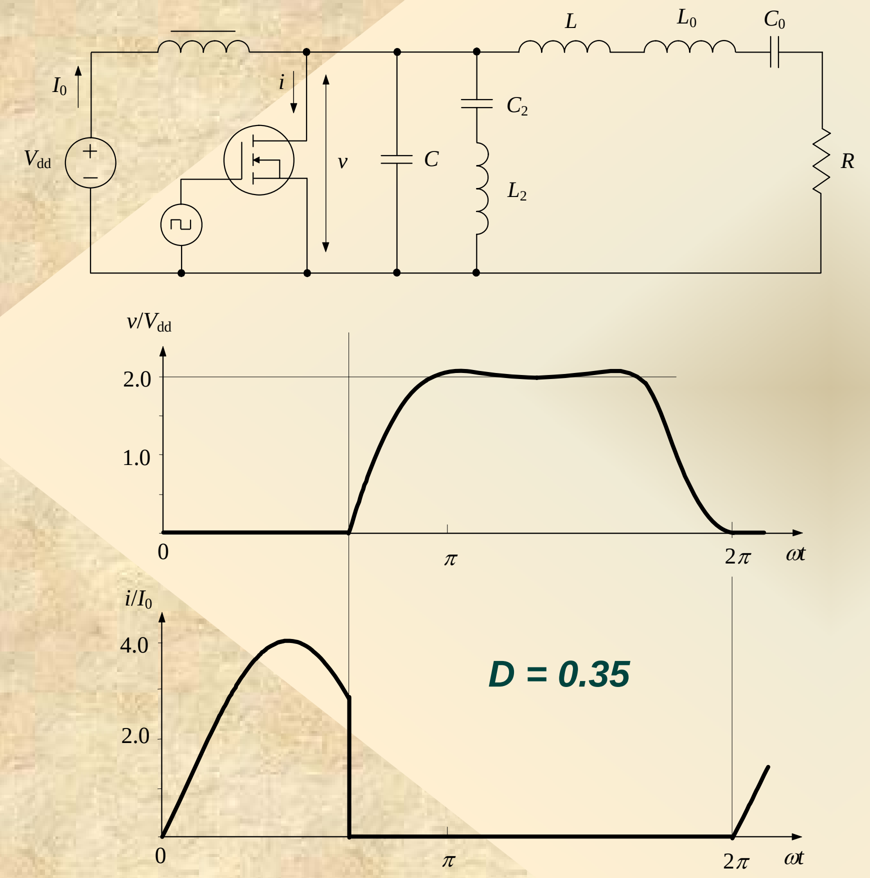
$$C = \frac{\sin^2\tau_d}{\pi}\frac{1}{\omega R}$$ - shunt capacitance

Optimum impedances at fundamental and harmonics for Class F, Class E and Class FE load networks

High-efficiency mode	f_0 (fundamental)	$2nf_0$ (even harmonics)	$(2n+1)f_0$ (odd harmonics)
Class F with quarterwave line		short	open
Class E with shunt capacitance			
Class FE with quarterwave line		short	

3. Design approximations with second-harmonic control ($Class\ EF_2$) and third-harmonic control ($Class\ E/F_3$)

Class E_2F (or F_2E) power amplifier



Idealized optimum conditions

$$v(\omega t)\big|_{\omega t=2\pi} = 0$$

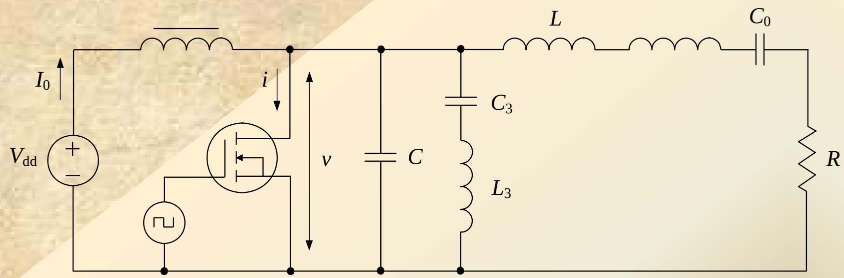
$$\left.\frac{dv(\omega t)}{d\omega t}\right|_{\omega t=2\pi} = 0$$

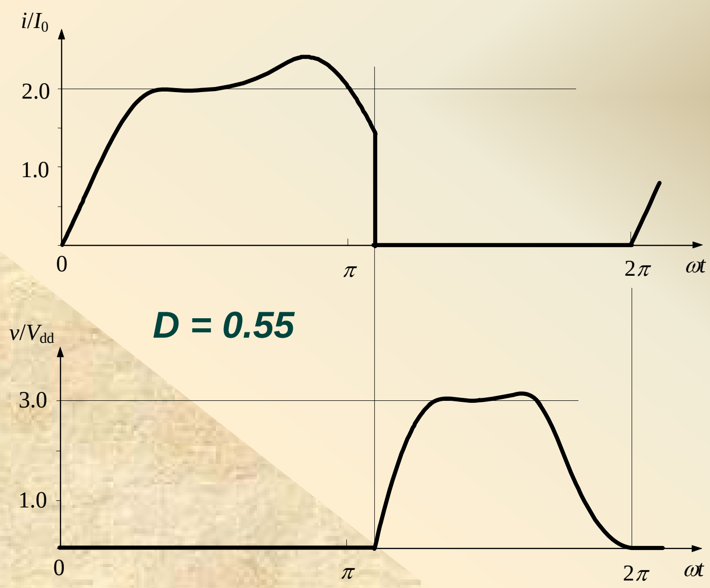
- ***transistor has zero saturation voltage, zero on-resistance, infinite off-resistance and its switching action is instantaneous and lossless***
- ***ideal Class E load network with shunt capacitance***
- ***series resonant L_2C_2 circuit tuned to second harmonic***

Z. Kaczmarczyk, "High-Efficiency Class E, EF_2 and E/F_3 Inverters," *IEEE Trans. Industrial Electronics*, vol. IE-53, pp. 1584-1593, Oct. 2006

3. Design approximations with second-harmonic control (Class EF$_2$) and third-harmonic control (Class E/F$_3$)

Class E/F$_3$ power amplifier





D = 0.55

Idealized optimum conditions

$$v(\omega t)\big|_{\omega t=2\pi} = 0$$

$$\left.\frac{dv(\omega t)}{d\omega t}\right|_{\omega t=2\pi} = 0$$

- ***transistor has zero saturation voltage, zero on-resistance, infinite off-resistance and its switching action is instantaneous and lossless***
- ***ideal Class E load network with shunt capacitance***
- ***series resonant L_3C_3 circuit tuned to third harmonic***

Z. Kaczmarczyk, "High-Efficiency Class E, EF$_2$ and E/F$_3$ Inverters," *IEEE Trans. Industrial Electronics*, vol. IE-53, pp. 1584-1593, Oct. 2006

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