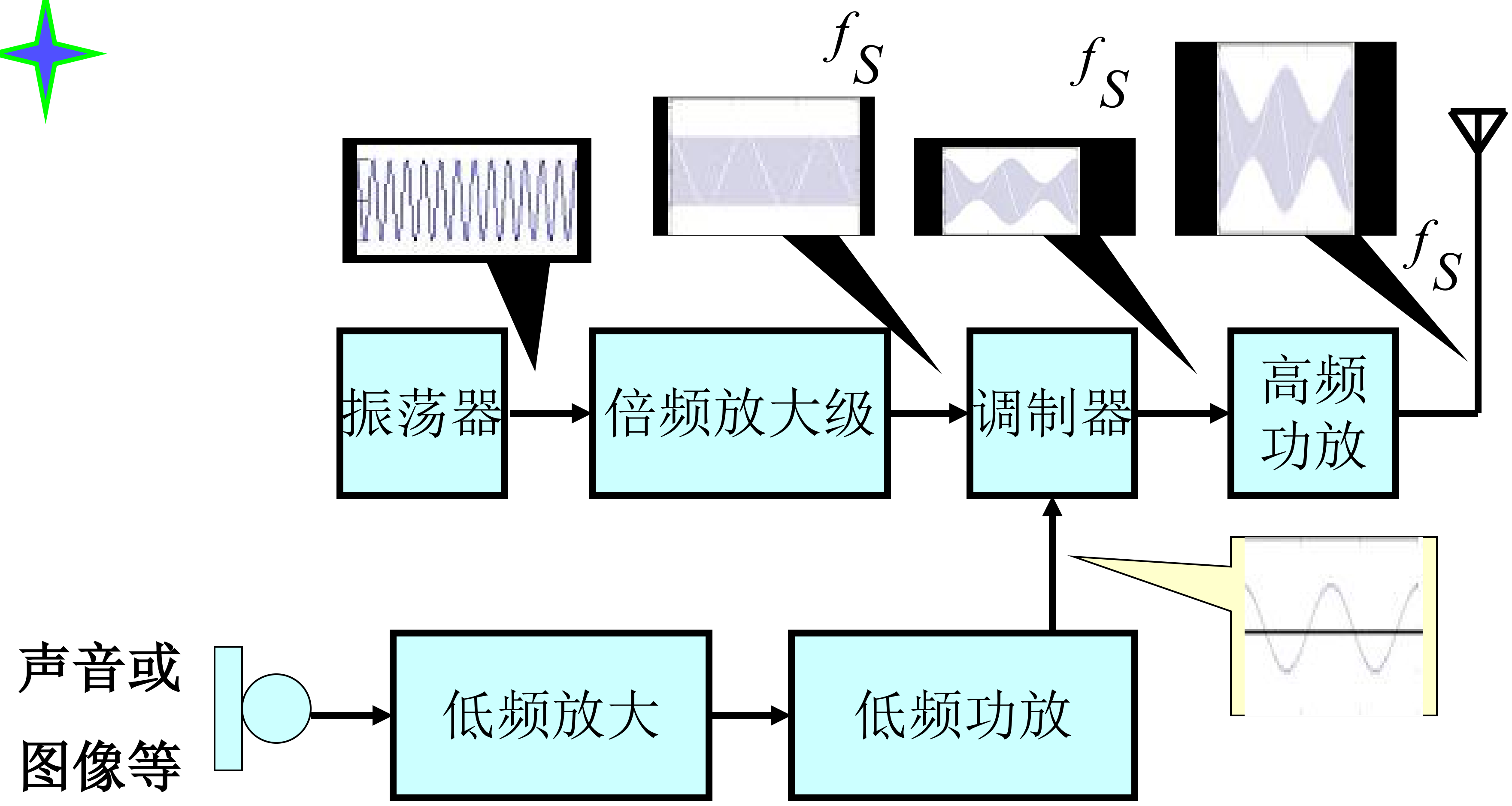
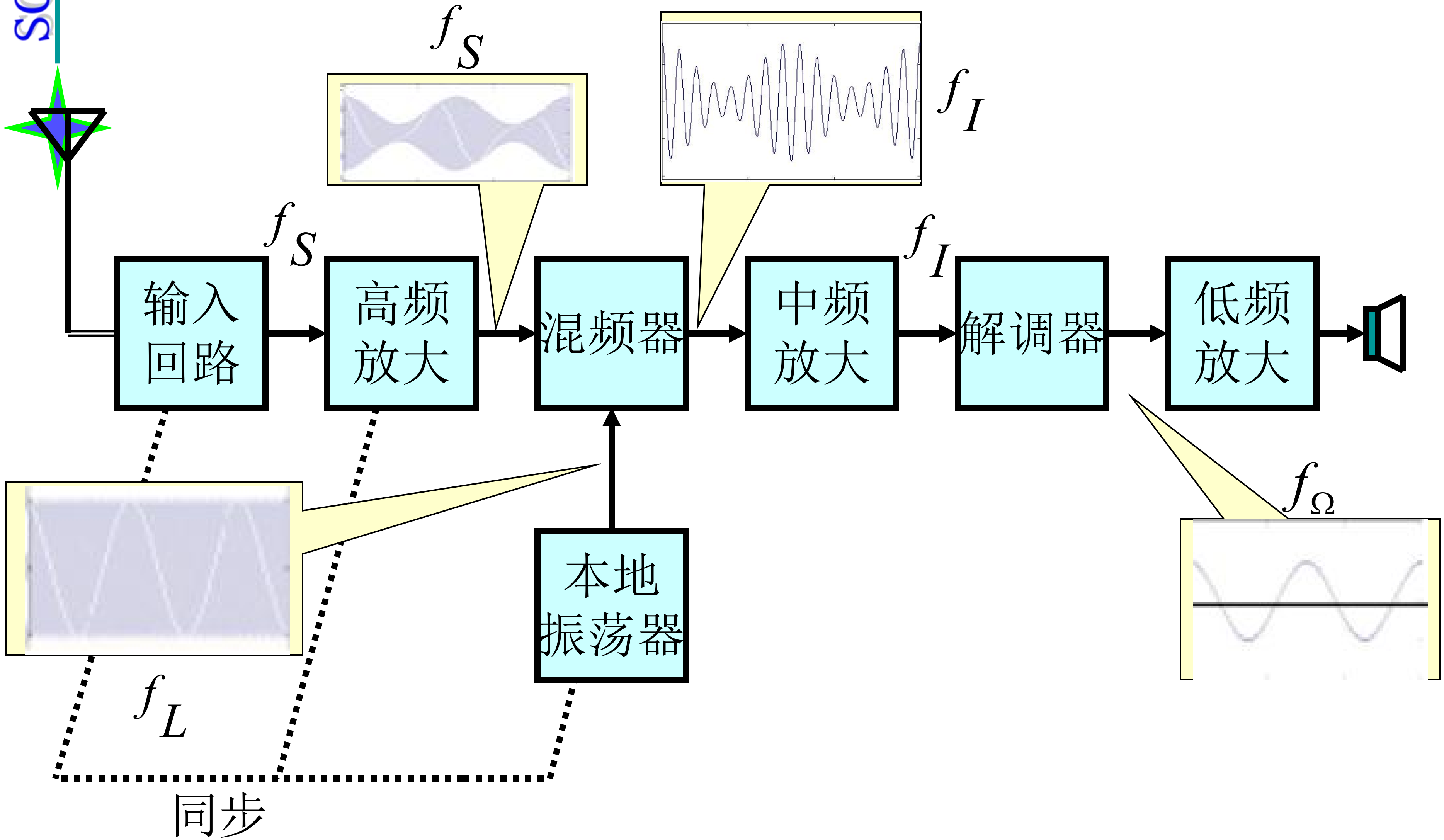


无线模拟发送系统框图



超外差式无线电接收系统框图

第5章　频率变换电路的特点及线性频谱搬移电路

5.1　概述

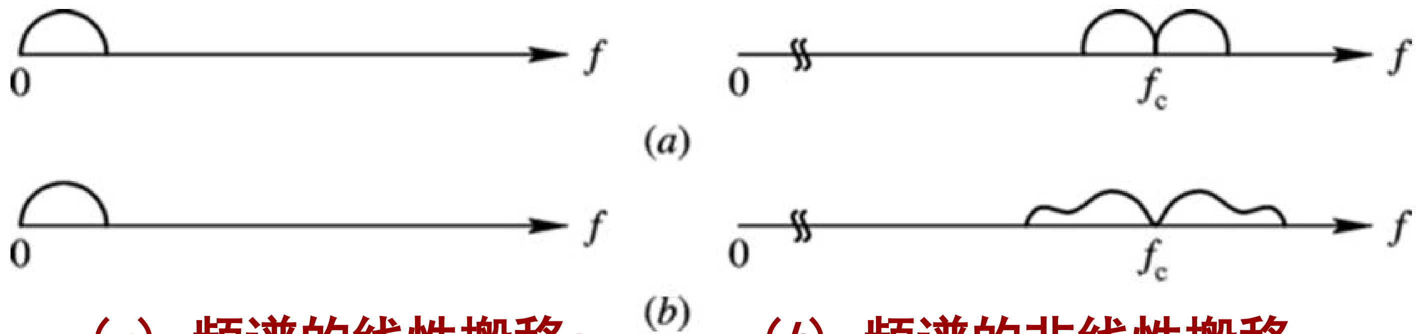
一、线性变换电路与非线性变换电路（时域和频域）

线性变换电路：其输出信号与输入信号具有某种特定的线性关系。

非线性变换电路（频率变换电路）的特点：其输出信号与输入信号不成线性关系。

二、频率变换电路的分类

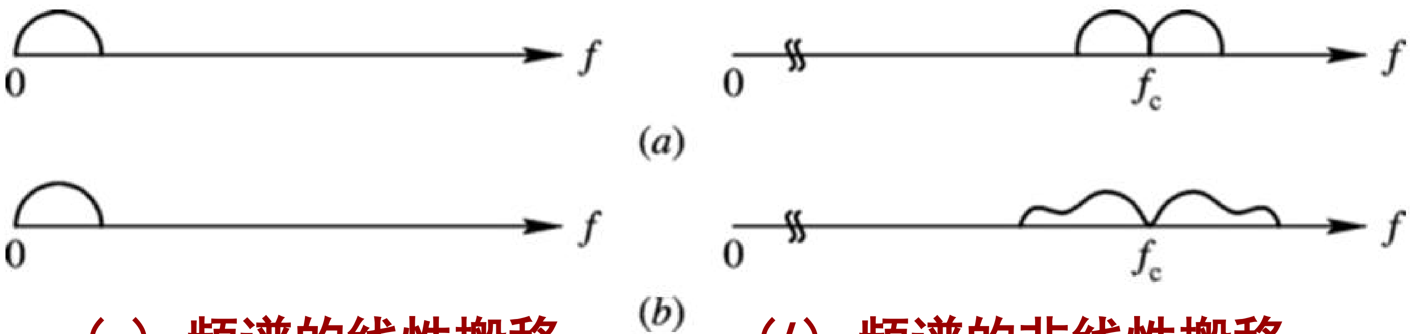
分类：
- 线性频率变换电路
- 非线性频率变换电路



（a）频谱的线性搬移；　（b）频谱的非线性搬移

线性频率变换电路的特点：信号频谱有简单的线性关系，或者说在频率轴上的搬移（频谱结构不变，相对幅度不变）（从频率结果来看，体现出来的就是加减或倍数关系），故又被称为频谱搬移电路。

非线性频率变换电路的特点：信号频谱不再是简单的线性关系，也不是频谱的搬移（频谱结构不相同），而是产生了某种非线性变换，如调频电路与鉴频电路。



（a）频谱的线性搬移；（b）频谱的非线性搬移

频率变换电路要采用非线性器件来实现。常用的非线性器件有：非线性电阻性器件（如二极管、晶体管）；非线性电容性器件（变容二极管）。

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5.2 非线性元器件频率变换特性的分析方法

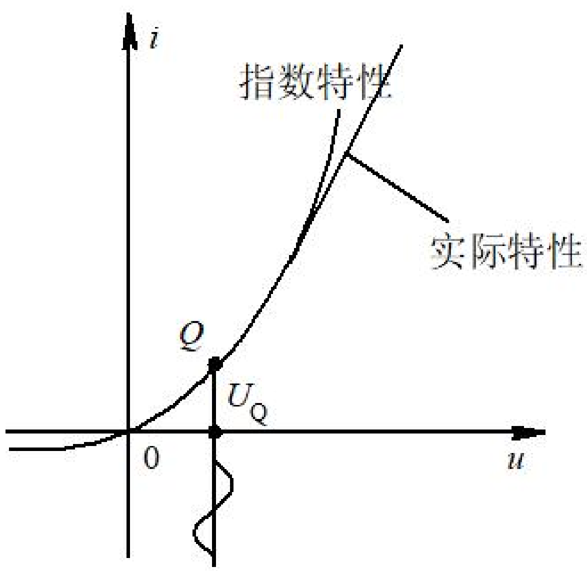
5.2.1 指数函数分析法

晶体二极管的正向伏安特性可用指数函数描述为:

$$i = I_s\left(e^{\frac{1}{U_T}u} - 1\right)$$

其中, 热电压U_T≈26mV(当T=300K时)

指数函数分析法仅适用于小信号工作状态下的二极管特性分析



晶体二极管的伏安特性

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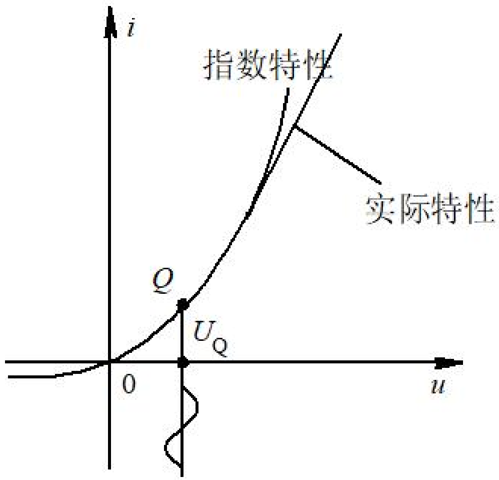
利用指数函数的幂级数展开式

$$e^x = 1 + x + \frac{1}{2!}x^2 + \ldots + \frac{1}{n!}x^n + \ldots$$

把式 $i = I_s(e^{\frac{1}{U_T}u} - 1)$ 展开，其中 $u = U_Q + U_S \cos\omega_s t$ **可得到**

$$i = I_s\left[\frac{U_Q}{U_T} + \frac{U_S}{U_T}\cos w_s t + \frac{1}{2U_T^2}(U_Q^2 + 2U_Q U_S \cos w_s t + U_s^2 \frac{1+\cos 2w_s t}{2}) + \ldots + \frac{1}{n!U_T^n}(U_Q + U_S \cos w_s t)^n + \bullet\bullet\bullet\right]$$

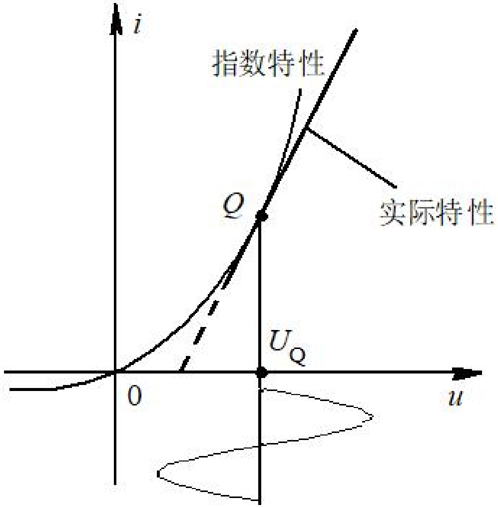


输出电流的频率分量可表示为：

$$\omega_0 = n\omega_s \qquad n = 0,1,2,\cdots$$

由于指数函数是一种超越函数, 所以这种方法又称为超越函数分析法。

5.2.2 折线函数分析法



当输入电压较大时, 晶体二极管的伏安特性可用两段折线来逼近，此时同晶体三极管的转移特性有相似的非线性特性，输出电流就是单频余弦波。由谐振功放分析结果可知, 当输入电压为直流偏压上迭加单频余弦波时, 二极管电流中的频率分量

$$\omega_0 = n\omega_s \qquad n = 0,1,2,\cdots$$

5.2.3 幂级数分析法

假设晶体二极管的非线性伏安特性可用函数表示为：

$$i = f(u)$$

此函数表示的是一条连续曲线，其在U_Q处存在各阶导数，其泰勒级数：

$$i = f(U_Q) + f'(U_Q)(u-U_Q) + \frac{f''(U_Q)}{2!}(u-U_Q)^2 + \bullet\bullet\bullet + \frac{f^{(n)}(U_Q)}{n!}(u-U_Q)^n + \bullet\bullet\bullet$$

$$= a_0 + a_1(u-U_Q) + a_2(u-U_Q) + \bullet\bullet\bullet + a_n(u-U_Q)^n + \bullet\bullet\bullet$$

式中 $a_n = \dfrac{f^{(n)}(U_Q)}{n!}$， n = 0，1，2，3，•••

当输入电压 $u = U_Q + U_s \cos\omega_s t$ 可求得输出电流

$$i = a_0 + a_1 U_s \cos\omega_s t + \frac{a_2 U_s^2}{2}(1+\cos 2\omega_s t) + \bullet\bullet\bullet + a_n U_s^n \cos^n \omega_s t + \bullet\bullet\bullet$$

可见输出电流中出现的频率分量仍为nw_s。

综上所述，非线性元器件的特性分析是建立在函数逼近（指数函数分析、折线函数分析、幂级数分析）的基础之上。当工作信号大小不同时，适用的函数可能不同，但与实际特性之间的误差都必须在工程所允许的范围之内。

幂级数分析法比较通用，因一般伏安特性都可以用某种函数形式表示

如果有多个输入信号，如两个，u_1和u_2，$u_{BE} = U_Q + u_1 + u_2$

$$i = f(u_{BE}) = f(U_Q + u_1 + u_2)$$ 其泰勒级数：

$$i = f(u_{BE}) = f(U_Q + u_1 + u_2)$$

$$= f(U_Q) + f'(U_Q)(u_1 + u_2) + \frac{1}{2!} f''(U_Q)(u_1 + u_2)^2 + \cdots + \frac{1}{n!} f^{(n)}(U_Q)(u_1 + u_2)^n + \cdots$$

$$= a_0 + a_1(u_1 + u_2) + a_2(u_1 + u_2)^2 + \cdots + a_n(u_1 + u_2)^n + \cdots$$

当 $u_1 = U_{1m}\cos\omega_1 t$，$u_2 = U_{2m}\cos\omega_2 t$

可求得输出电流中频率分量的表达式

$$\boldsymbol{\omega}_0 = |\pm \boldsymbol{p}\boldsymbol{\omega}_1 \pm \boldsymbol{q}\boldsymbol{\omega}_2| \qquad \boldsymbol{p}、\boldsymbol{q} = 0,1,2,\cdots$$

输出信号频率是两个不同输入信号频率各次谐波的各种不同组合，且包含有直流分量。

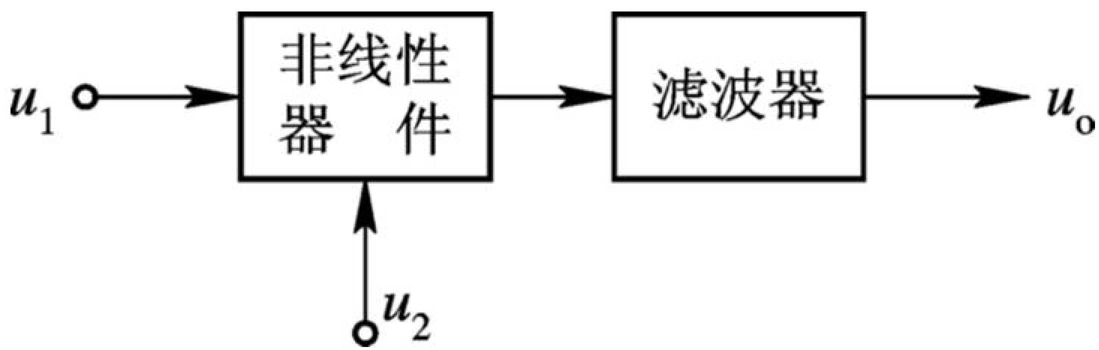
线性频谱搬移的目的通常就是得到基波分量的组合，只要有两个输入信号的乘积项可以得到基本分量组合。

$$i = f(u_{BE}) = f(U_Q + u_1 + u_2)$$
$$= f(U_Q) + f'(U_Q)(u_1 + u_2) + \frac{1}{2!} f''(U_Q)(u_1 + u_2)^2 + \cdots + \frac{1}{n!} f^{(n)}(U_Q)(u_1 + u_2)^n + \cdots$$
$$= a_0 + a_1(u_1 + u_2) + a_2(u_1 + u_2)^2 + \cdots + a_n(u_1 + u_2)^n + \cdots$$

因为输出电流中频率分量的表达式

$$\boldsymbol{\omega}_0 = \left| \pm \boldsymbol{p}\boldsymbol{\omega}_1 \pm \boldsymbol{q}\boldsymbol{\omega}_2 \right| \qquad \boldsymbol{p}、\boldsymbol{q} = 0,1,2,\cdots$$

不只含有基波分量的组合，还有很多的无用频率组合。



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如果 $u_1 >> u_2$，$u_{BE} = U_Q + u_1 + u_2$

其泰勒级数:

$$i = f(u_{BE}) = f(U_Q + u_1 + u_2)$$

$$= f(U_Q + u_1) + f'(U_Q + u_1)u_2 + \frac{1}{2!}f''(U_Q + u_1)u_2^2 + \cdots + \frac{1}{n!}f^{(n)}(U_Q + u_1)u_2^n + \cdots$$

$$\approx f(U_Q + u_1) + f'(U_Q + u_1)u_2$$

$$\approx I_0(t) + g(t)u_2$$

时变静态电流

时变电导或时变跨导

其中 $I_0(t) = f(U_Q + u_1)$，$g(t) = f'(U_Q + u_1)$

$I_0(t)$与$g(t)$均是与u_2无关的参数，故i_C与u_2可看成一种线性关系，但是$I_0(t)$与$g(t)$又是随时间变化的，所以将这种工作状态称为线性时变工作状态。

线性时变法是一般采用的分析方法。

$$i = f(u_{BE}) = f(U_Q + u_1 + u_2) \approx f(U_Q + u_1) + f'(U_Q + u_1)u_2 \approx I_0(t) + g(t)u_2$$

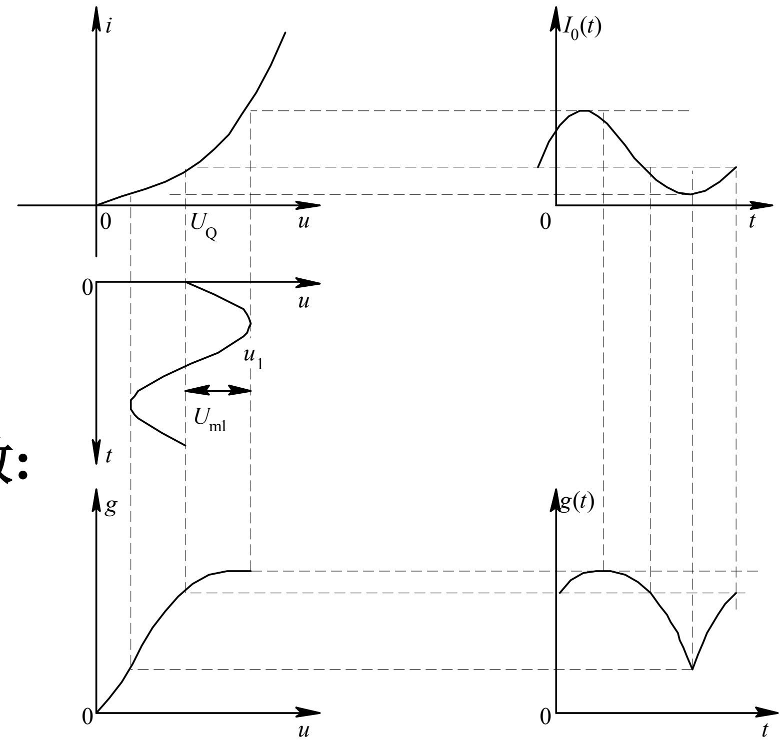
当 $u_1 = U_{1m}\cos\omega_1 t$，$u_2 = U_{2m}\cos\omega_2 t$ 时

$I_0(t)$是周期性变化的，可以展开为傅里叶级数:

$$I_0(t) = I_{00} + \sum_{n=1}^{\infty} I_{on}\cos n w_1 t$$

其中 $I_{on} = \dfrac{1}{\pi}\int_{-\pi}^{+\pi} I_o(t)\cos n\omega_1 t\, d\omega_1 t$

同理 $g(t) = g_0 + \sum_{n=1}^{\infty} g_n \cos n\omega_1 t$



线性时变工作状态时 $I_0(t)$与$g(t)$的波形

$$i = I_{00} + \sum_{n=1}^{\infty} I_{on}\cos n w_1 t + \left[g_0 + \sum_{n=1}^{\infty} g_n\cos n w_1 t\right] U_{m2}\cos w_2 t$$

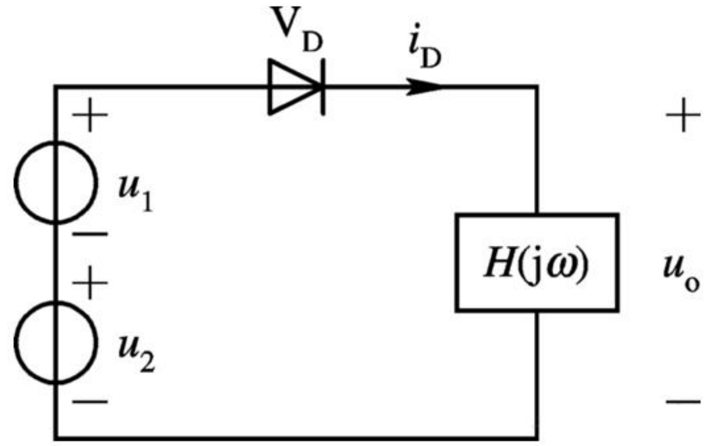
可看出, i中含有直流分量、ω_1的各次谐波分量以及$|\pm n\omega_1 \pm \omega_2|$分量 (n=0, 1, 2, …)。与式$\omega_o = |\pm p\omega_1 \pm q\omega_2|$ 比较, 减少了许多组合频率分量。

5.3 线性频率搬移/变换电路

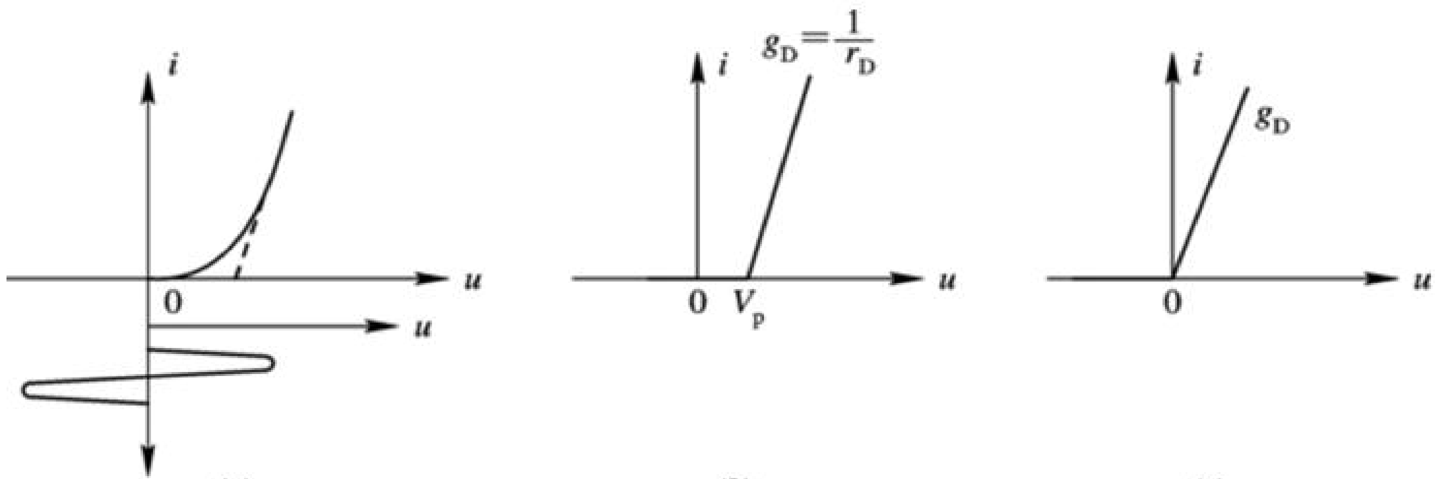
5.3.1 二极管电路

1、 单二极管电路

$u_2 = U_2\cos\omega_2 t$　　　$u_D = u_1 + u_2$



$U_2 >> U_1$; 且有 $U_2 > 0.5$ V



(a)　　(b)　　(c)

$$i_D = \begin{cases} g_D u_D & u_D \geq V_p \\ 0 & u_D < V_p \end{cases}$$

$$i_D = \begin{cases} g_D u_D & u_2 \geq 0 \\ 0 & u_2 < 0 \end{cases}$$

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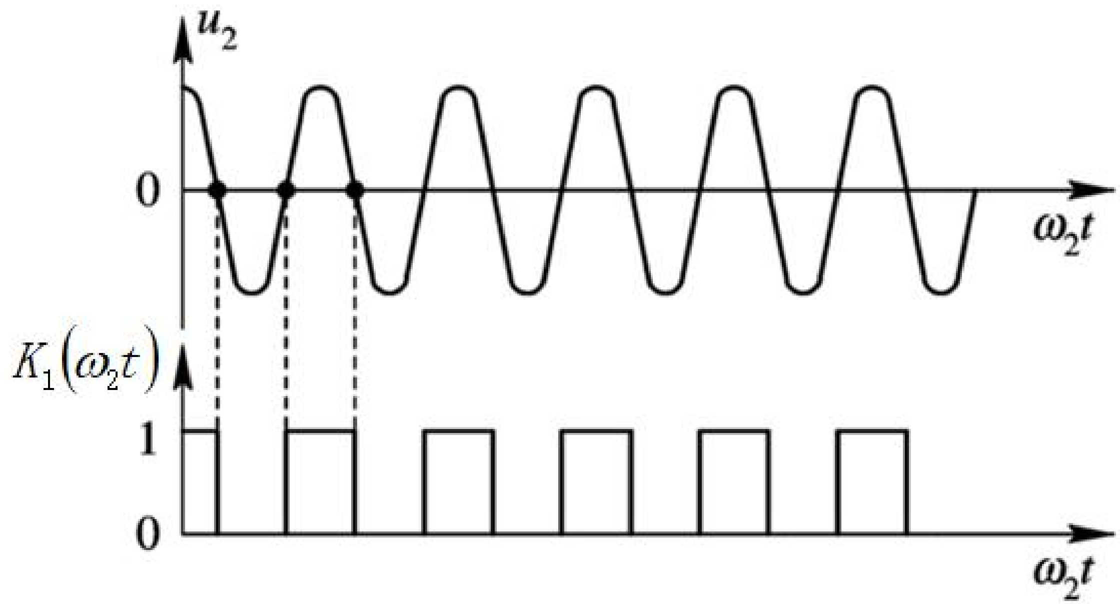
1、 单二极管电路



$$u_D=u_1+u_2$$

$$i_D=\begin{cases} g_D u_D & u_2 \geq 0 \\ 0 & u_2 < 0 \end{cases}$$

$$K_1(\omega_2 t)=\frac{1}{2}+\frac{2}{\pi}\cos\omega_2 t-\frac{2}{3\pi}\cos 3\omega_2 t+\frac{2}{5\pi}\cos 5\omega_2 t-\cdots+(-1)^{n+1}\frac{2}{(2n-1)\pi}\cos(2n-1)\omega_2 t+\cdots$$

$$i_D=g_D u_D K_1(\omega_2 t)=g_D\left[\frac{1}{2}+\frac{2}{\pi}\cos\omega_2 t-\frac{2}{3\pi}\cos 3\omega_2 t+\frac{2}{5\pi}\cos 5\omega_2 t-\cdots\right]u_D$$

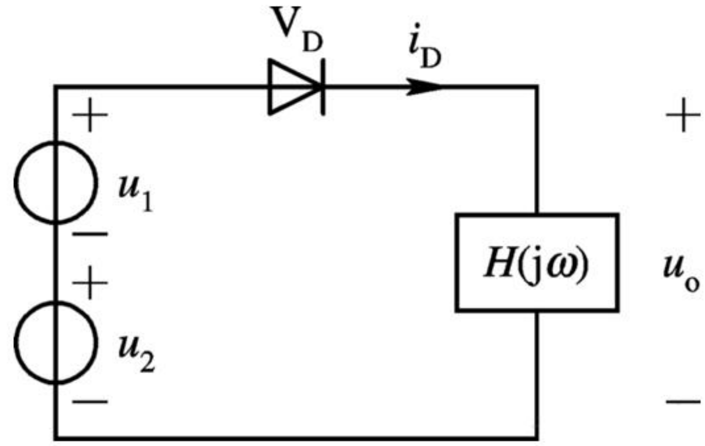
$u_D = u_1 + u_2$

$$i_D = g_D\left[\frac{1}{2} + \frac{2}{\pi}\cos\omega_2 t - \frac{2}{3\pi}\cos 3\omega_2 t + \frac{2}{5\pi}\cos 5\omega_2 t - \cdots\right]u_D$$

若$u_1 = U_1\cos\omega_1 t$，为单一频率信号，代入上式有

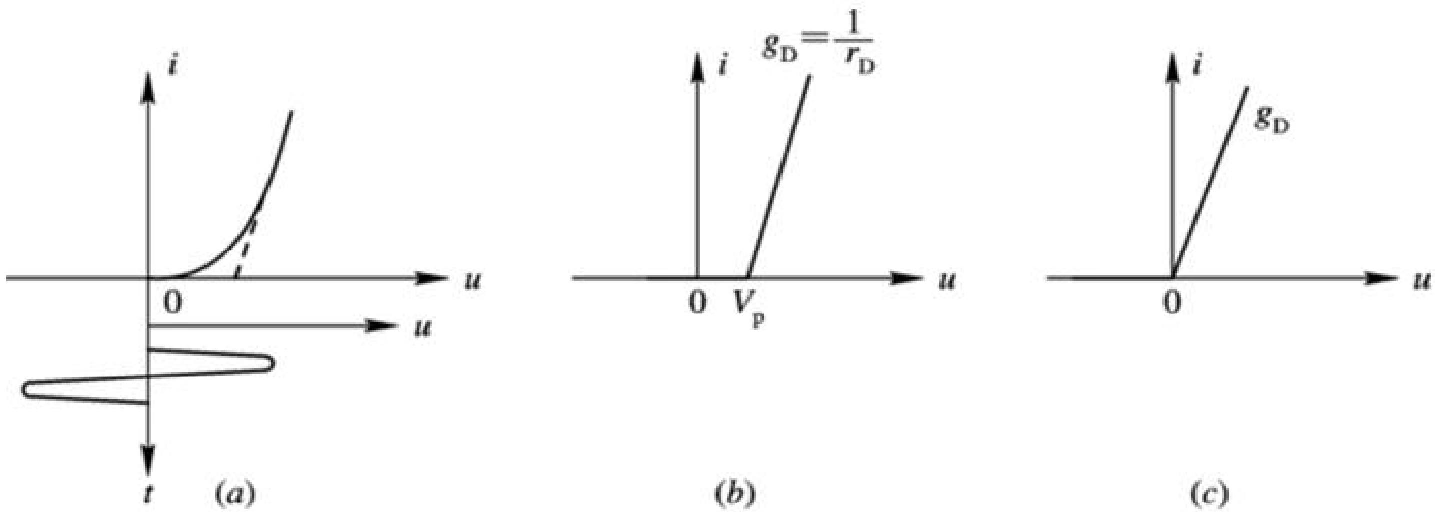
$$\begin{aligned}
i_D = {} & \frac{g_D}{\pi}U_2 + \frac{g_D}{2}U_1\cos\omega_1 t + \frac{g_D}{2}U_2\cos\omega_2 t + \frac{2}{3\pi}g_D U_2\cos 2\omega_2 t \\
& - \frac{2}{15\pi}g_D U_2\cos 4\omega_2 t + \cdots + \frac{1}{\pi}g_D U_1\cos(\omega_2 - \omega_1)t \\
& + \frac{1}{\pi}g_D U_1\cos(\omega_2 + \omega_1)t - \frac{1}{3\pi}g_D U_1\cos(3\omega_2 - \omega_1)t \\
& - \frac{1}{3\pi}g_D U_1\cos(3\omega_2 + \omega_1)t + \frac{1}{5\pi}g_D U_1\cos(5\omega_2 - \omega_1)t \\
& + \frac{1}{5\pi}g_D U_1\cos(5\omega_2 - \omega_1)t + \cdots
\end{aligned}$$

$$u_2 = U_2\cos\omega_2 t$$



若$u_D = U_Q + u_1 + u_2$

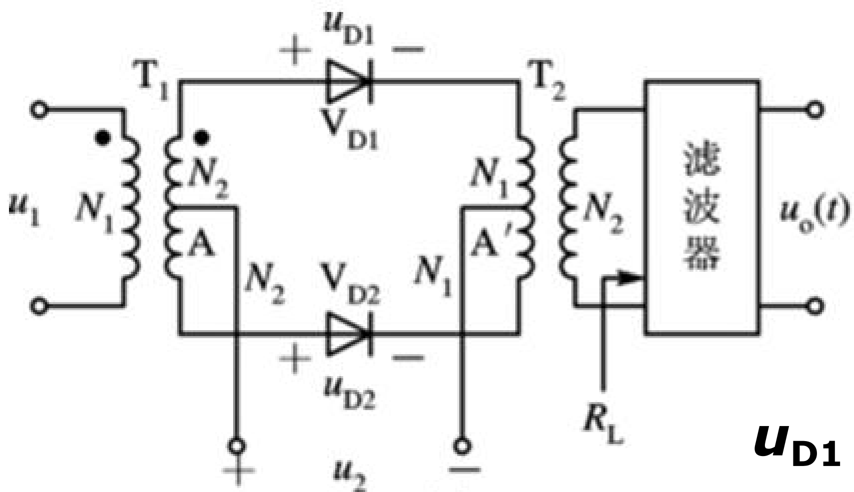
$U_2 >> U_1$



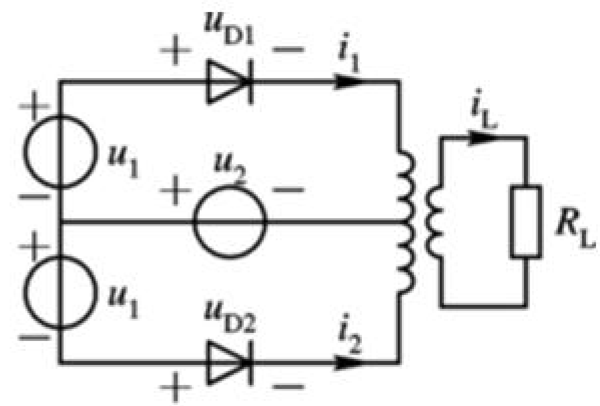
$$i_D = \begin{cases} g_D u_D & u_D \geq V_p \\ 0 & u_D < V_p \end{cases}$$

$$i_D = \begin{cases} g_D u_D & u_2 \geq 0 \\ 0 & u_2 < 0 \end{cases}$$

2、二极管平衡电路



(a)



(b)

$$u_{D1}=u_2+u_1$$

$$u_{D2}=u_2-u_1$$

$$i_1=g_1(t)u_{D1}=g_DK_1(\omega_2t)\ (u_2+u_1)$$

$$i_2=g_1(t)u_{D2}=g_DK_1(\omega_2t)\ (u_2-u_1)$$

$$i_L=i_{L1}-i_{L2}=i_1-i_2$$

$$i_L=2g_DK_1(\omega_2t)u_1$$

考虑$u_1=U_1\cos\omega_1t$，代入上式可得

$$i_L=g_DU_1\cos\omega_1t+\frac{2}{\pi}g_DU_1\cos(\omega_2+\omega_1)t+\frac{2}{\pi}g_DU_1\cos(\omega_2-\omega_1)t$$

$$-\frac{2}{3\pi}g_DU_1\cos(3\omega_2+\omega_1)t-\frac{2}{3\pi}g_DU_1\cos(3\omega_2-\omega_1)t+\cdots$$

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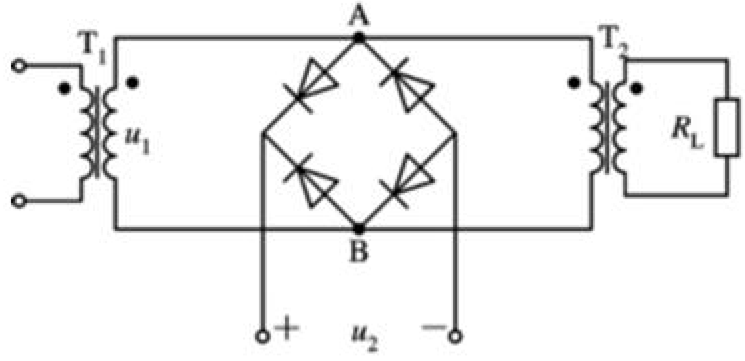
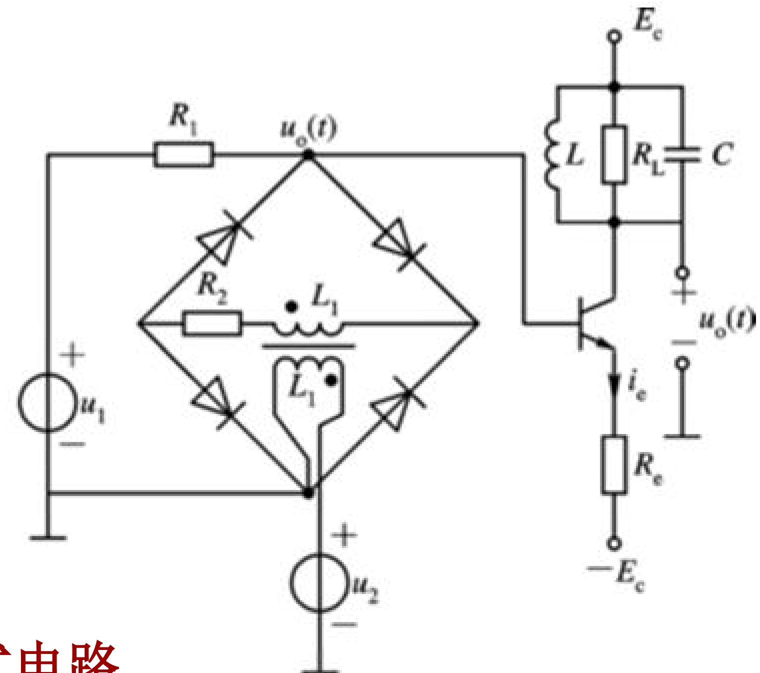
3、二极管平衡电路



(a)

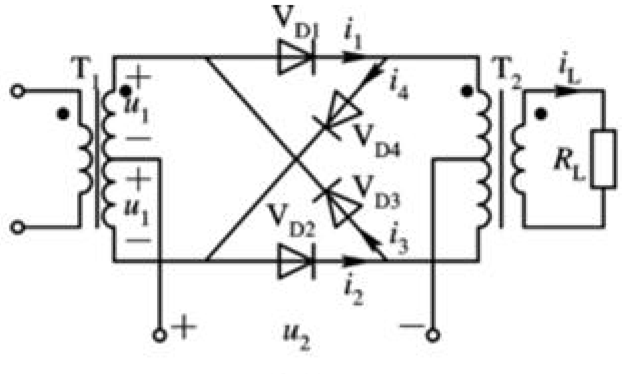


(b)

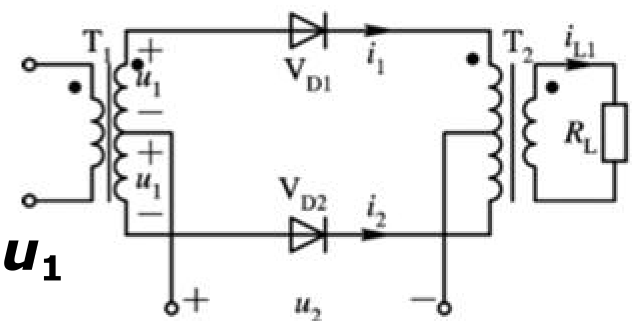
二极管桥式电路

$$u_{AB}=K_1(\omega_2 t)u_1$$

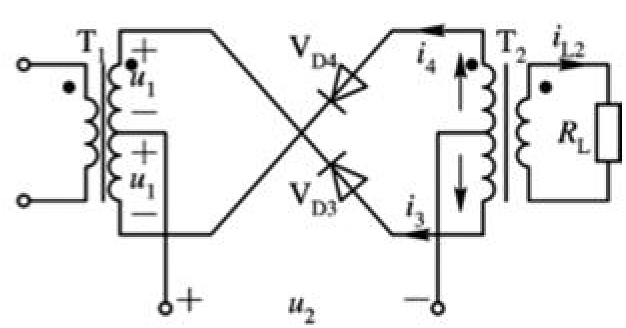
3、二极管环形电路



(a)



(b)



(c)

$u_{D1} = u_2 + u_1$

$u_{D2} = u_2 - u_1$

$u_{D3} = -u_2 - u_1$

$u_{D4} = -u_2 + u_1$

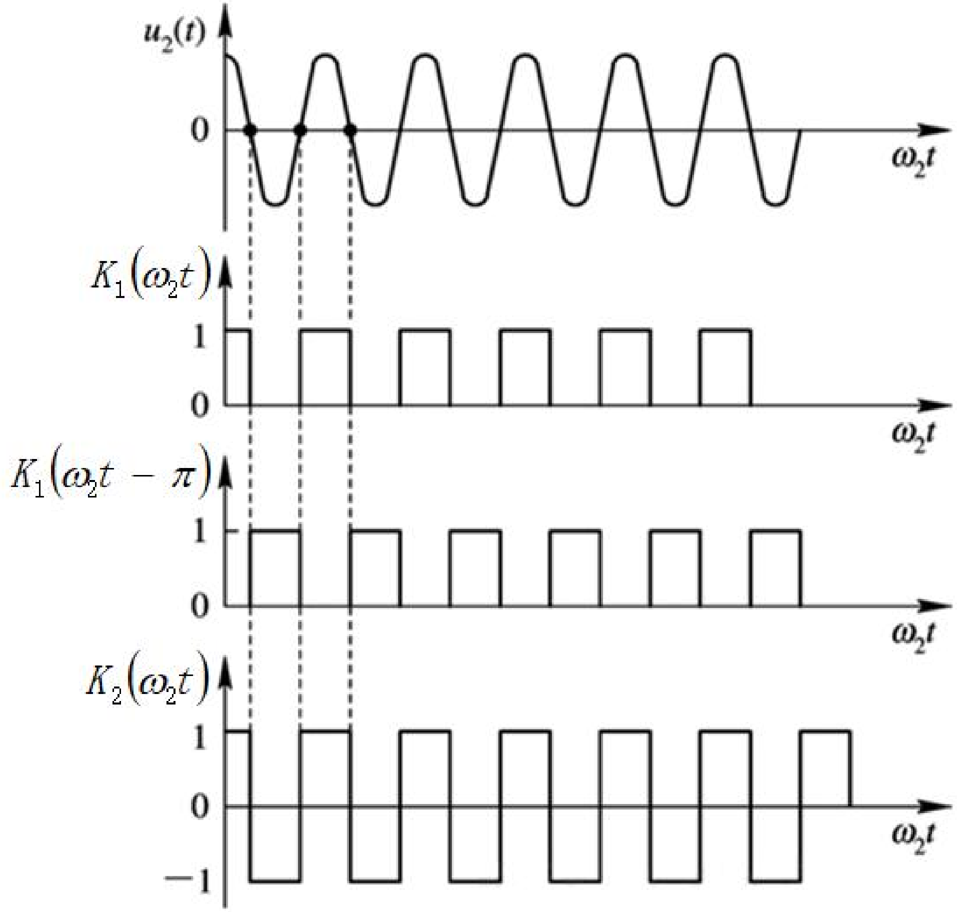
$i_L = i_{L1} + i_{L2} = (i_1 - i_2) + (i_3 - i_4)$

$$i_{L1} = 2g_D K_1(\omega_2 t)u_1,\quad i_{L2} = -2g_D K_1(\omega_2 t - \pi)u_1$$

$$i_L = 2g_D[K_1(\omega_2 t) - K_1(\omega_2 t - \pi)]u_1 = 2g_D K_2(\omega_2 t)u_1$$

SCU

3、二极管环形电路

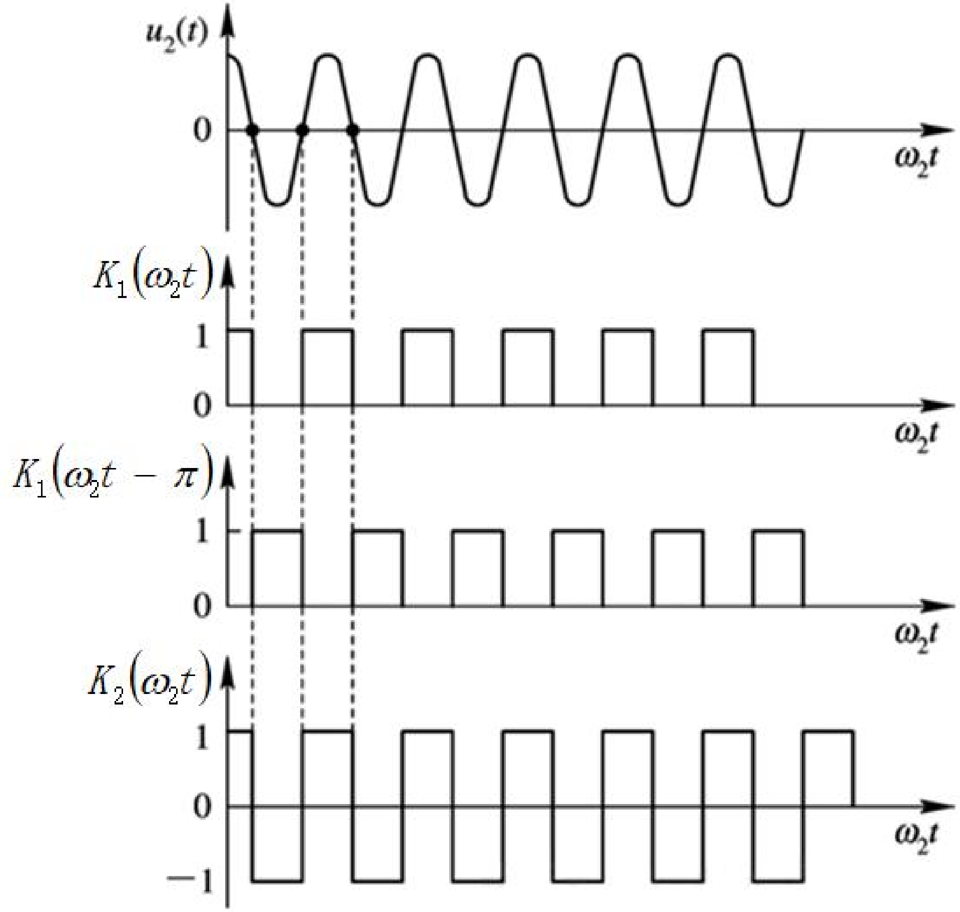


环形电路的开关函数波形图

$$i_{L1}=2g_D K_1(\omega_2 t)u_1,\quad i_{L2}=-2g_D K_1(\omega_2 t-\pi)u_1$$

$$i_L=2g_D[K_1(\omega_2 t)-K_1(\omega_2 t-\pi)]u_1=2g_D K_2(\omega_2 t)u_1$$

3、二极管环形电路

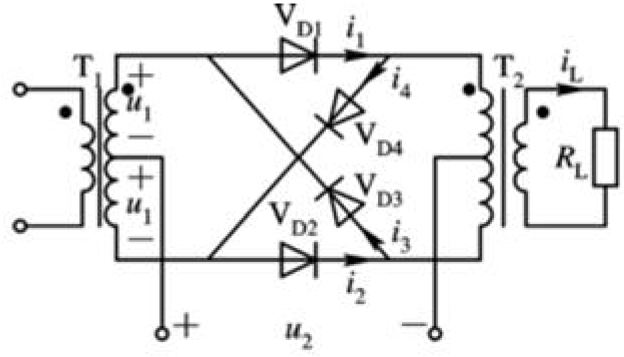


环形电路的开关函数波形图

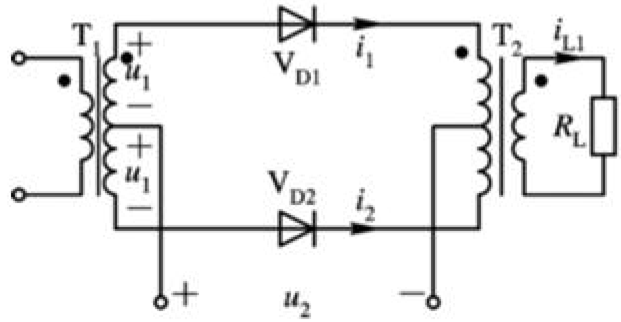
$$K_2(\omega_2 t)=\frac{4}{\pi}\cos\omega_2 t-\frac{4}{3\pi}\cos 3\omega_2 t+\frac{4}{5\pi}\cos 5\omega_2 t+\cdots$$

$$+(-1)^{n+1}\frac{4}{(2n+1)\pi}\cos(2n+1)\omega_2 t+\cdots$$

3、二极管环形电路



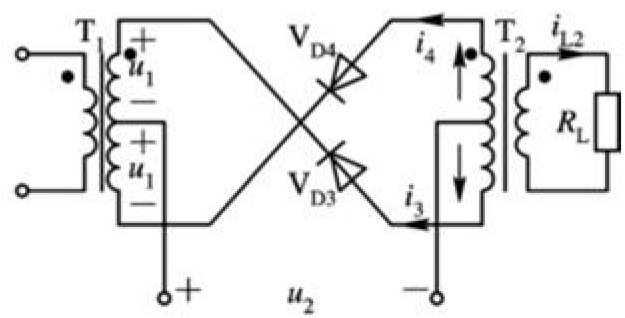
(a)



$u_{D1}=u_2+u_1$

$u_{D2}=u_2-u_1$

(b)



$u_{D3}=-u_2-u_1$

(c)

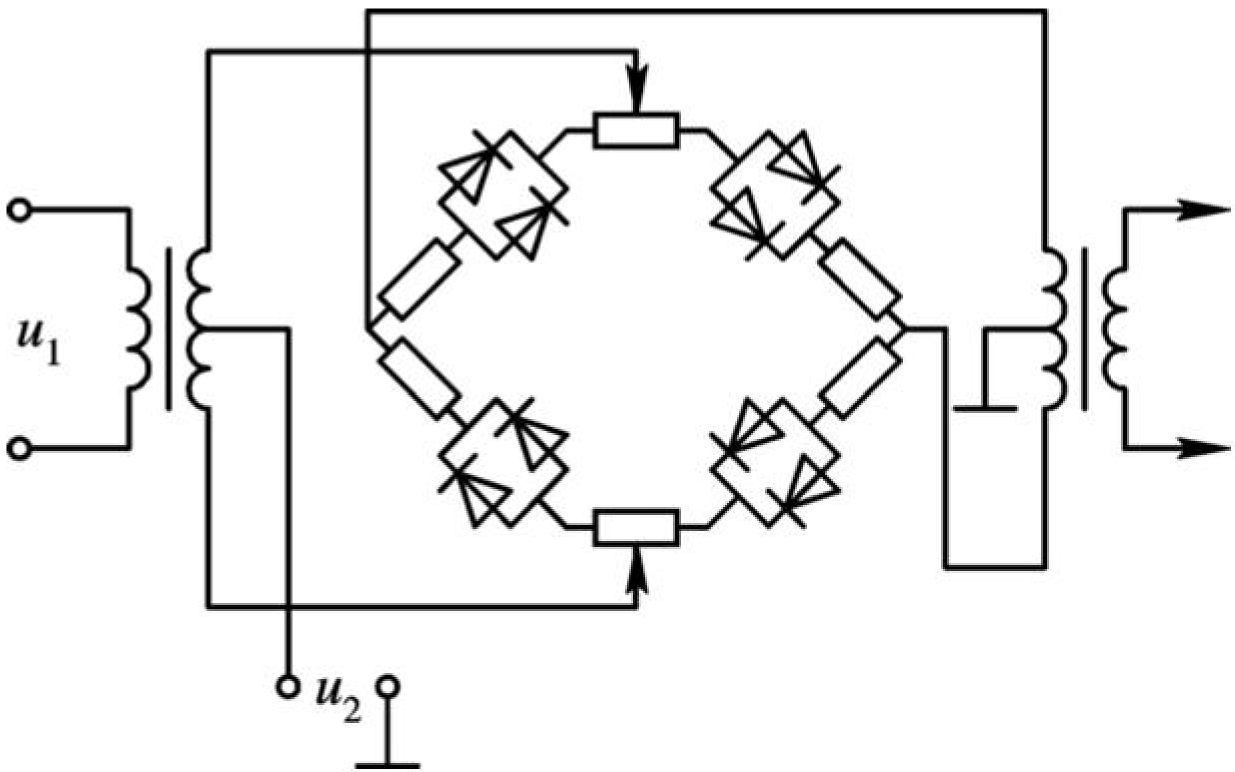
$$i_L = 2g_D K_2(\omega_2 t)u_1$$

$u_{D4}=-u_2+u_1$

当$u_1=U_1\cos\omega_1 t$时

$$\begin{aligned} i_L =& \frac{4}{\pi}g_D U_1\cos(\omega_2+\omega_1)t+\frac{4}{\pi}g_D U_1\cos(\omega_2-\omega_1)t \\ & -\frac{4}{3\pi}g_D U_1\cos(3\omega_2+\omega_1)t-\frac{4}{3\pi}g_D U_1\cos(3\omega_2-\omega_1)t \\ & +\frac{4}{5\pi}g_D U_1\cos(5\omega_2+\omega_1)t+\frac{4}{5\pi}g_D U_1\cos(5\omega_2-\omega_1)t\cdots \end{aligned}$$

3、二极管环形电路

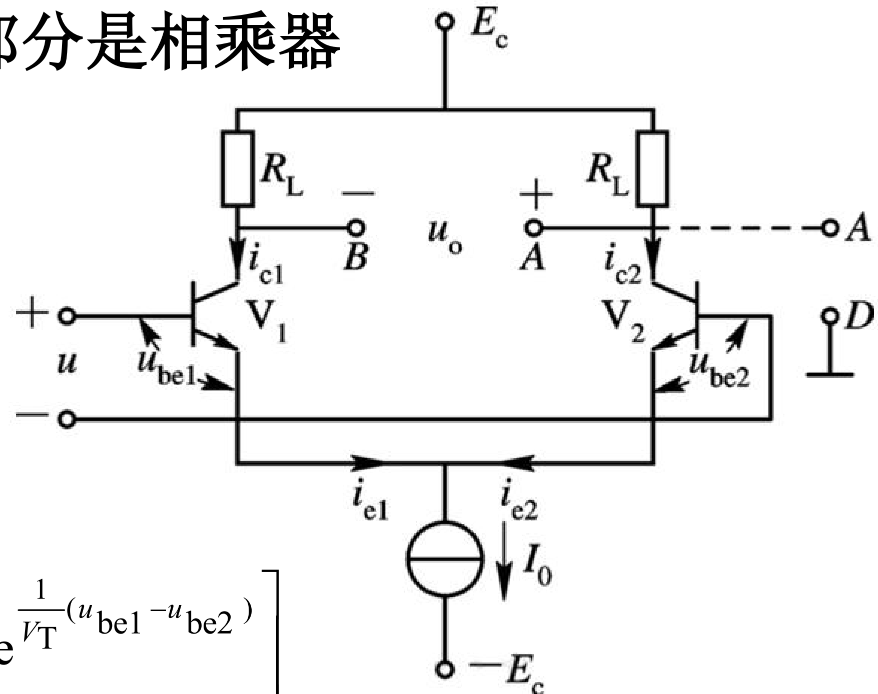


实际的环形电路

5.3.2 差分对管电路

频谱搬移电路的核心部分是相乘器

1、单差分对电路



差分对原理电路

$$i_{c1} \approx I_s e^{\frac{q}{kT}u_{be1}} = I_s e^{\frac{u_{be1}}{V_T}}$$

$$i_{c2} \approx I_s e^{\frac{q}{kT}u_{be2}} = I_s e^{\frac{u_{be2}}{V_T}}$$

$$I_0 = i_{c1} + i_{c2} = I_s e^{\frac{u_{be1}}{V_T}} + I_s e^{\frac{u_{be2}}{V_T}} = i_{c2}\left[1 + e^{\frac{1}{V_T}(u_{be1} - u_{be2})}\right]$$

$$= i_{c2}(1 + e^{\frac{u}{V_T}}) \qquad i_{c2} = \frac{I_o}{1 + e^{\frac{u}{V_T}}}$$

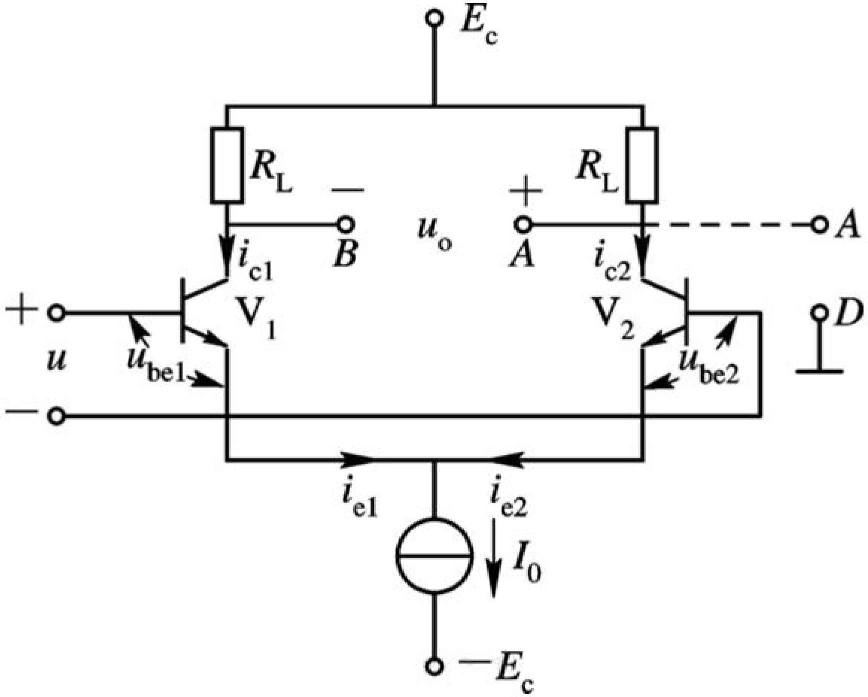
$$i_{c1} = \frac{I_o}{1 + e^{-\frac{u}{V_T}}}$$

$$i_{c1} - \frac{I_o}{2} = \frac{I_o}{2}\left(\frac{2}{1 + e^{-\frac{u}{V_T}}}\right) - \frac{I_o}{2} = \frac{I_o}{2} th\left(\frac{u}{2V_T}\right)$$

1、单差分对电路

$$i_{c1} = \frac{I_o}{2} + \frac{I_o}{2} th\left(\frac{u}{2V_T}\right)$$

$$i_{c2} = \frac{I_o}{2} - \frac{I_o}{2} th\left(\frac{u}{2V_T}\right)$$

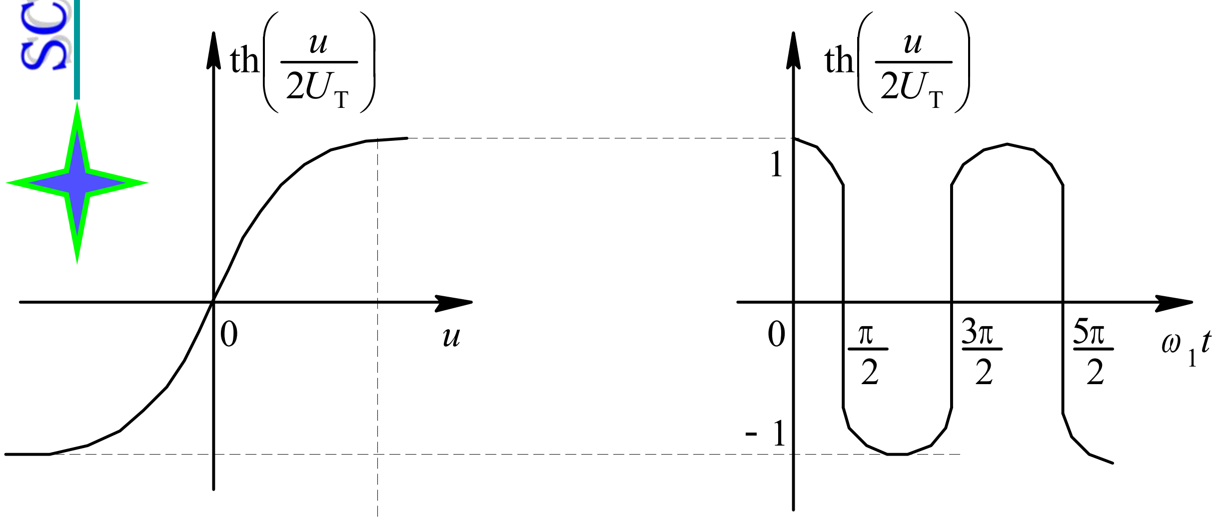


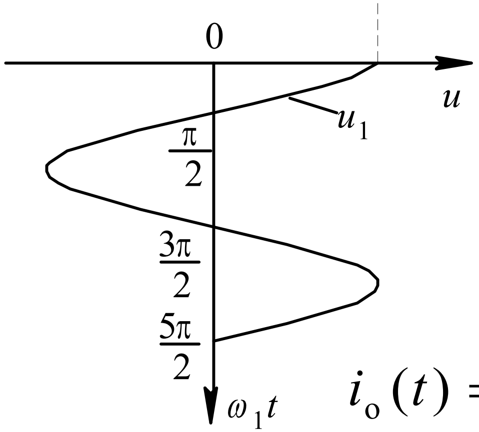
差分对原理电路

$$u_o = u_{c2} - u_{c1} = (E_c - i_{c2}R_L) - (E_c - i_{c1}R_L)$$

$$= R_L(i_{c1} - i_{c2}) = R_L I_o th\left(\frac{u}{2V_T}\right)$$

$$i_o = i_{c1} - i_{c2} = I_o th\left(\frac{u}{2V_T}\right)$$





1、单差分对电路

$$i_o = i_{c1} - i_{c2} = I_o th\left(\frac{u}{2V_T}\right)$$

当$u=U_1 \cos\omega_1 t$时，令 $x = \frac{U_1}{U_T}$

$$i_o(t) = I_o[\beta_1(x)\cos\omega_1 t + \beta_3(x)\cos 3\omega_1 t + \beta_5(x)\cos 5\omega_1 t + \cdots]$$

$$= I_o \sum_{n=1}^{\infty} \beta_{2n-1}(x)\cos(2n-1)\omega_1 t$$

$$\beta_{2n-1}(x) = \frac{1}{\pi}\int_{-\pi}^{\pi} th\left(\frac{x}{2}\cos\omega_1 t\right)\cos(2n-1)\omega_1 t\,d\omega_1 t$$

1、单差分对电路

$$u_A = U_1 \cos\omega_1 t$$

考虑 $|u_A| < 26$ mV时，有

$$i_o(t) \approx \frac{E_e}{R_e}\left(1 + \frac{u_B}{E_e}\right)\frac{u_A}{2V_T}$$

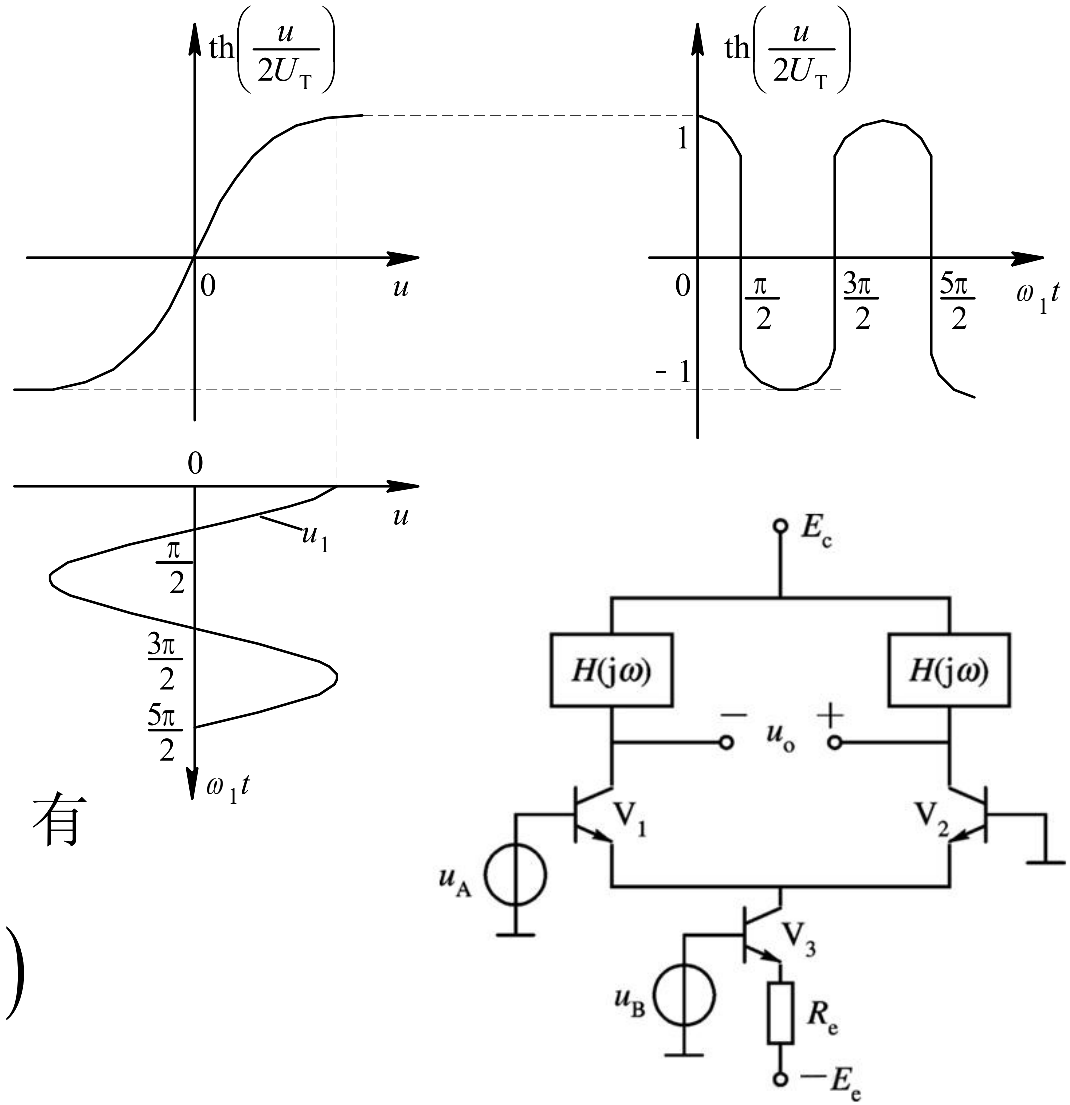
考虑 $|u_A| > 100$ mV时，

$$th\left(\frac{u_A}{2V_T}\right)$$近似一个双向开关，有

$$i_o(t) = I_o(t) K_2(\omega_1 t)$$

考虑 $|u_A|$ 为其它时，

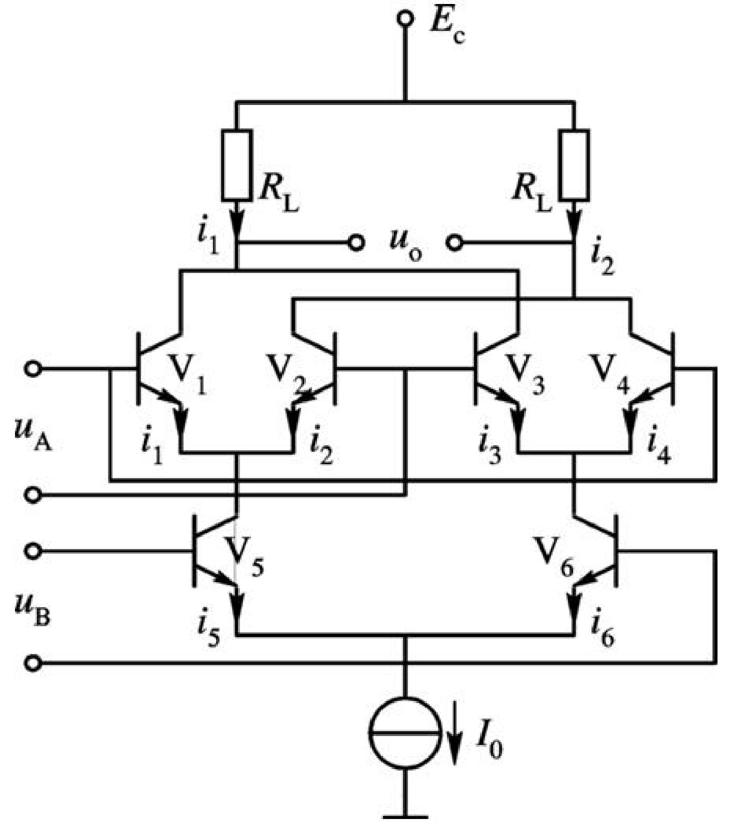
$$i_o(t) = I_o(t) th\left(\frac{u_A}{2V_T}\right) \approx \frac{E_e}{R_e}\left(1 + \frac{u_B}{E_e}\right) th\left(\frac{u_A}{2V_T}\right)$$



2、双差分对电路

$$i_1 - i_2 = i_5 th\left(\frac{u_A}{2V_T}\right)$$

$$i_4 - i_3 = i_6 th\left(\frac{u_A}{2V_T}\right)$$



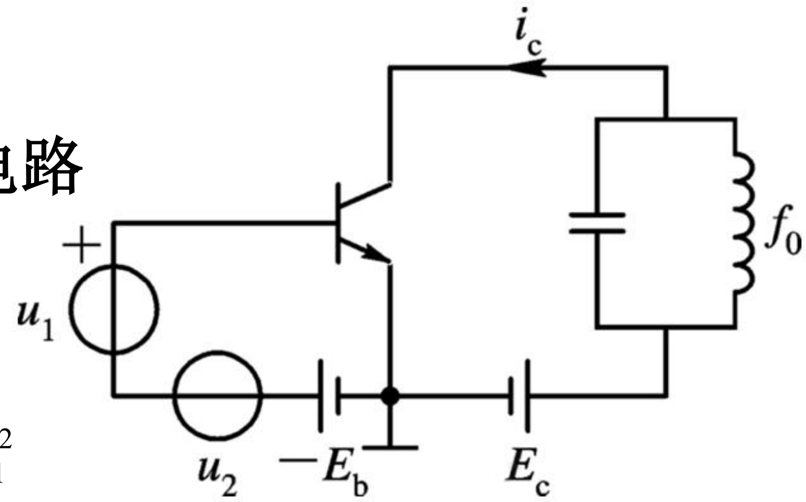
双差分对电路

$$i_5 - i_6 = I_0 th\left(\frac{u_B}{2V_T}\right)$$

$$i_o = i_1 - i_2 - (i_4 - i_3) = I_0 th\left(\frac{u_A}{2V_T}\right) th\left(\frac{u_B}{2V_T}\right)$$

5.3.3 晶体管频率搬移电路

1、晶体三极管频谱线性搬移电路



$i_c=f(u_{BE})=f(u_1+u_2+E_b)=f\,[E_b(t)+u_1]$

$$i_c=f[E_b(t)]+f'[E_b(t)]u_1+\frac{1}{2}f''[E_b(t)]u_1^2+\frac{1}{3!}f'''[E_b(t)]u_1^3+\cdots+\frac{1}{n!}f^{(n)}[E_b(t)]u_1^n+\cdots$$

$$f[E_b(t)]=f(u_{BE})\Big|_{u=E_b(t)}=I_{c0}(t)$$

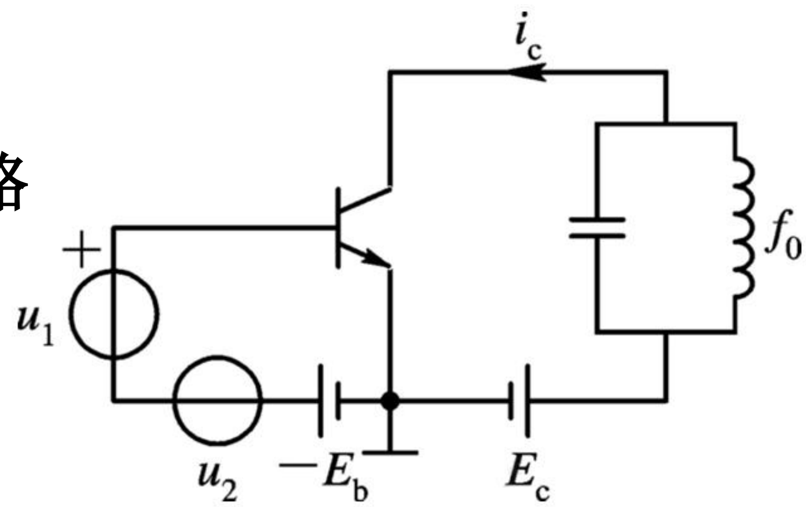
$$I_{c0}(t)=I_{c00}+I_{c01}\cos\omega_2 t+I_{c02}\cos 2\omega_2 t+\cdots$$

$$f'[E_b(t)]=\frac{\mathrm{d}i_c}{\mathrm{d}u_{BE}}\Big|_{u_{BE}=E_b(t)}=\frac{\mathrm{d}f(u_{BE})}{\mathrm{d}u_{BE}}\Big|_{u_{BE}=E_b(t)}=g_m(t)$$

$g_m(t)=g_{m0}+g_{m1}\cos\omega_2 t+g_{m2}\cos 2\omega_2 t+\cdots$

SCU

1、晶体三极管频谱线性搬移电路



$i_c=f(u_{BE})=f(u_1+u_2+E_b)=f\left[E_b(t)+u_1\right]$

$$i_c = f[E_b(t)] + f'[E_b(t)]u_1 + \frac{1}{2} f''[E_b(t)]u_1^2 + \frac{1}{3!} f'''[E_b(t)]u_1^3 + \cdots + \frac{1}{n!} f^{(n)}[E_b(t)]u_1^n + \cdots$$

$$I_{c0}(t) = I_{c00} + I_{c01}\cos\omega_2 t + I_{c02}\cos 2\omega_2 t + \cdots$$

$$g_m(t)=g_{m0}+g_{m1}\cos\omega_2 t+g_{m2}\cos 2\omega_2 t+\cdots$$

$$\begin{aligned} i_c &\approx I_{c0}(t) + g_m(t)u_1 \\ &\approx I_{c00} + I_{c01}\cos\omega_2 t + I_{c02}\cos 2\omega_2 t + \cdots \\ &\quad + (g_{m0} + g_{m1}\cos\omega_2 t + g_{m2}\cos 2\omega_2 t + \cdots)U_1\cos\omega_1 t \end{aligned}$$

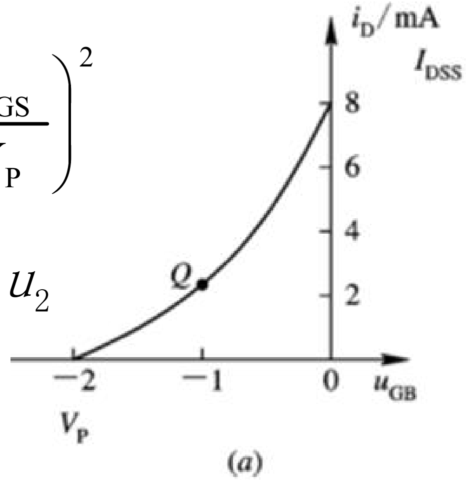
2、场效应管频谱线性搬移电路

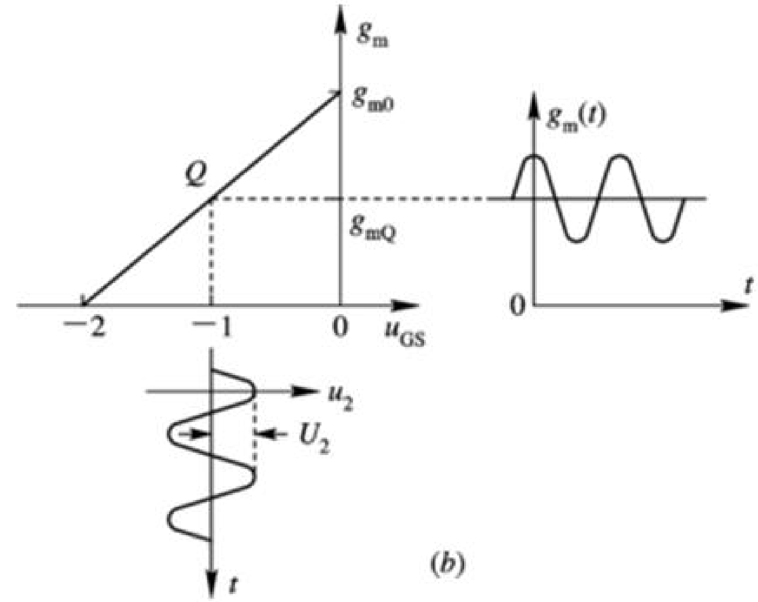
$$i_D = I_{DSS}\left(1-\frac{u_{GS}}{V_P}\right)^2$$

$$u_{GS} = E_{GS} + u_1 + u_2$$

$$u_1 = U_1 \cos \omega_1 t$$

$$u_2 = U_2 \cos \omega_2 t \text{ 且 } U_1 \ll U_2$$





结型场效应管的电流与跨导特性

对应于u_{GS}的时变跨导为 $$g_m(t) = -\frac{2I_{DSS}}{V_P}\left(1-\frac{E_{GS}}{V_P}\right) + 2I_{DSS}\frac{U_2}{V_P^2}\cos \omega_2 t$$

$$i_D = I_o(t) + g_m(t)u_1$$

$$= I_{DSS}\left(1-\frac{E_{GS}+U_2\cos \omega_2 t}{V_P}\right)^2$$

$$+\left[-\frac{2I_{DSS}}{V_P}\left(1-\frac{E_{GS}}{V_P}\right) + 2I_{DSS}\frac{U_2}{V_P^2}\cos \omega_2 t\right]U_1 \cos \omega_1 t$$

作业

5.1，5.2，5.3，5.4