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Study of the impedance matching in radio frequency discharge excited Z-Fold waveguide CO_2 laser

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Abstract:

Equivalent circuit of Γ matching network is applied to measure the impedances of an RF-excited partial Z-fold waveguide CO_2 laser. In addition, the design criteria are discussed for the selection of the coil inductances and laser head characteristics for optimum power transfer.

Keyword: Waveguide CO_2 laser, impedance matching , Γ matching network , RF excited.

Introduction:

Matching design requires knowledge of the discharge impedance and its dependences on the input RF power, gas pressure and operation mode. Hence measurements of the discharge impedance are important to achieve a model for the Z-fold CO_2 waveguide laser and to calculate the plasma impedance [1].

In order to achieve the maximum laser efficiency it is necessary to arrange experimental conditions such that the highest possible fraction of the power generated by the RF power supply is dissipated in the laser discharge. An essential prerequisite for achieving this goal of maximum power transfer is that the impedance of the laser structure, including the discharge, be matched to the generator [2] .In general, this condition is achieved when the impedance seen by the source looking into the load (discharge) is the complex conjugate of the impedance seen by the load looking back into the power generator .However, the impedance of a transverse RF excited discharge does not in general satisfy the condition. For RF generators in common use, the output impedance is usually real and equal to 50 Ω [3].Thus, in order to achieve optimum power transfer, or even to strike a discharge, it is necessary to interpose an impedance- matching network between generator and load to effect the impedance transformation.

In this paper the problem of the efficient transfer of radio frequency power from a generator to a laser discharge head has been analysed for one particular type of matching circuit (equivalent circuit of Γ matching network) and examine its application to radio frequency discharge partial Z-fold waveguide CO_2 laser.

Laser head and Γ matching network:

We have designed and constructed such a compact tunable electrooptically Q-switched RF excited partial Z-fold CO_2 waveguide laser with two channels (designed and manufactured in Chinese National Key Laboratory of Tunable laser Technology), a structure of which is shown in Figure (1-a). The laser is designed around a metal ceramic sandwich waveguide, which has a 2.25x2.25 mm^2 cross-section [3, 4]. The laser structure has two channels, partial Z-fold channel and single channel. The two channels are excited by the same RF source and placed within a water –cooled stainless vacuum housing, which incorporate a RF feed through to enable power to be transmitted to the waveguide. The distance of two channels is 20 mm. The partial Z-fold channel is 3x460 mm in length and the single one is 460 mm.

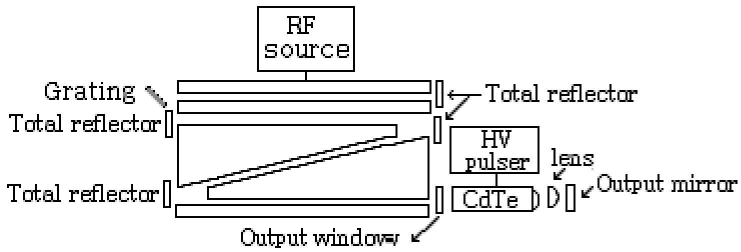


Figure (1-a) Structure of the CO_2 laser

We designed equivalent Case III waveguide resonator for partial Z-fold channel. The partial Z-fold channel is used as transmitter laser and the single one is used as local oscillator laser. By using two different channels, most of the RF power is transmitted to the partial Z-fold channel. Due to the structure of common electrodes and close distance between the two channels the voltages on the two channels are nearly equal. When the RF input power is varied, the variations of gas refractive index and cavity length of the two channels are nearly the same direction. So the relative frequency stability of the laser from the two channels is less disturbed by the variation of RF power and circumstance influences[5-7]. It can be predicted that the relative frequency stability between two lasers excited by the same RF generator is much better than for two independent, separate lasers.

Laser head and Γ matching network:

To model the discharge plasma, we consider the motion of an electron cloud in an oscillatory electric field of angular frequency, ω , in a gaseous medium without boundaries [8] .Electronic motion can be described by the equation

$$m\dot{\upsilon}_D + m\upsilon_D \upsilon = -eEe^{i\omega t} \qquad \text{……………………..(1)}$$

Where m and e are the electron mass and charge respectively, υ_D is the drift velocity and υ is the electron collision frequency. This can be solved for υ_D, from which current $I(t)$ may be written as

$$I(t) = \frac{ne^2 AVe^{iwt}}{m(iw+\upsilon)d} \qquad \text{...................................(2)}$$

where n is the electron density, A is the discharge area, d the electrode separation and V the discharge voltage .From equation (2) we have for the impedance Z

$$Z = R_g + iX_d = md(\upsilon + iw)/ne^2 A \qquad \text{………………….(3)}$$

whre R_g and X_d are the real and imaginary parts of the discharge impedance .Equating real and imaginary parts in equation (3) we have

$$R_g = m\upsilon d / ne^2 A \qquad \text{……………………..(4)}$$

and

$$X_d = (\omega / \upsilon) R_g \qquad \text{………………………(5)}$$

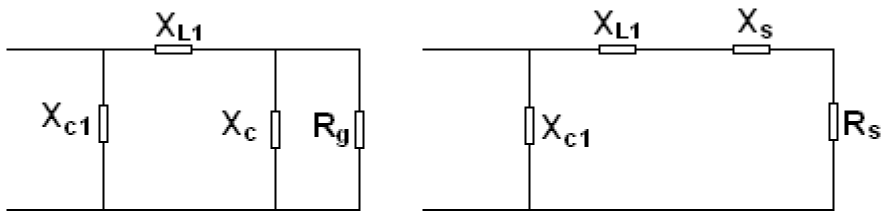


Figure (1-b). Equivalent circuit of Γ matching network

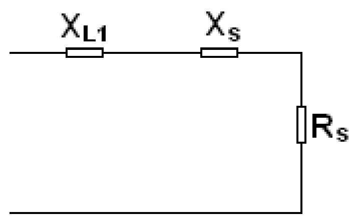


Figure (1-c). Simplified circuit of matching network

In addition, the resistor R_g in figure (1-b) is used to represent all dissipative loss terms other than the discharge itself. This includes contact resistance losses, ohmic and radiation losses, while X_{c1} in figure (1-b) represents the capacitance introduced by the feedthrough.

The total impedance of the overall circuit Z_s is given by

$$Z_s = \left(\frac{1}{R_g} - \frac{1}{iX_c}\right)^{-1} = \frac{X_c^2 R_g}{R_g^2 + X_c^2} - \frac{iX_c R_g^2}{R_g^2 + X_c^2} \qquad \text{……………(6)}$$

where $X_c = \dfrac{1}{\omega C}$ and

$$X_s = \frac{X_c R_g^2}{R_g^2 + X_c^2} \qquad \text{………………………(7)}$$

$$R_s = \frac{X_c^2 R_g}{R_g^2 + X_c^2} \qquad \text{………………………(8)}$$

For the laser waveguide Z-fold head matching network

$$\left(\frac{1}{iX_{L1} + R_s - iX_s} + \frac{i}{X_c}\right)^{-1} = 50 \qquad \text{……………………(9)}$$

where $X_L = \omega L1$ and

$$X_{c1} = \frac{50R_s}{\sqrt{R_s(50-R_s)}} \qquad \text{………………..(10)}$$

$$X_{L1} = \pm\sqrt{R_s(50-R_s)} + X_s \qquad \text{………………..(11)}$$

For maximum power transfer, we require that the real part of equation (6) be equal to (50 Ω),while the imaginary part be zero.
we can therefore write

$$\frac{N^2 X_0^2 R}{R^2 + X^2} = 50 \qquad \text{………………(12)}$$

$$\frac{N X_0 X}{R^2 + X^2} = 1 \qquad \text{………………(13)}$$

where $R = R_s + X_c$, $X_0 = \omega L_0$, $L_0 = XL_1$, *and* $X = \omega L_0 - X_s$
Equation (12) and (13) may be solved for X_0 and N to yield

$$X_0 = X_s + \frac{R^{\frac{3}{2}}}{\sqrt{50-R}} \qquad \text{…………………(14)}$$

and

$$N = \frac{50}{X_s[(50-R)/R]^{0.5} + R} \qquad \text{……………..…..(15)}$$

Equation (14) and (15) enable us to calculate the value of the total inductance (N) and the splitting ratio necessary for perfect impedance matching at a given frequency.

To consider the transfer power from the generator to the discharge .We define the total impedance (matching network and laser head) Z_T and voltage reflection coefficient S .

$$S = \left|\frac{50 - Z_T}{50 + Z_T}\right| \qquad \text{………………………(16)}$$

If P_0 is the power generated by the power supply, the power P_L available to the laser head is given by

$$P_L = P_0(1 - S^2) \qquad \text{……..………….(17)}$$

From figure (1-b) and figure (1-c) the power P_d dissipated in the discharge resistance expressed as

$$P_d = P_0(1 - S^2)(\frac{R_g}{r(1+\omega^2 C^2 R_g^2) + R_g} \qquad \text{..………..…(18)}$$

We define the power transfer coefficient η_{RF} as the fractional power delivered to the discharge load, so that

$$\eta_{RF} = P_d / P_0 = (1 - S^2)(\frac{R_g}{r(1+\omega^2 C^2 R_g^2) + R_g}) \qquad \text{……(19)}$$

A fundamental requirement of the matching circuit for laser Z-fold excitation is that it provides sufficient voltage gain to enable the gas break down and the RF discharge to be established .We define the voltage gain, G , as the ratio of the voltage vector at the discharge electrodes to the voltage vector at the input to the matching circuit .It can be shown that G is given by the equation

$$G = \left| \frac{(1+S)Z_s}{Z_s + (r + i\omega L1)} \right| \qquad \text{……..……..(20)}$$

Results and Discussion:

In certain power ranges R_g varies with the magnitude of the RF power input[9] and in addition is strongly dependent on generator frequency[10].However , for the present purposes, we will assume that R_g has only some stable value when the discharge is struck.

Figure 2 shows the variation of the reflection coefficient and power transfer coefficient with the discharge resistance for C = 9pF and f =120 MHz and where the total inductance and the splitting ratio have been chosen for the case of $R_g = 400\Omega$ and $R_g^2 \omega R_s^2 \geq 1$.If the discharge resistance change from this value, the reflection increases and the power transfer coefficient deceases rapidly. This is not surprising because the optimum splitting ratio is a strong function of the discharge resistance. Consequently, a small amount of change in the discharge resistance will destroy the established matching condition and a fraction of the input power will be rejected.

The voltage gain for the case of C = 9pF and f =120MHz is given in figure 3 as a function of the discharge resistance. Voltage gain plays an important role in the initiation and control of the discharge.

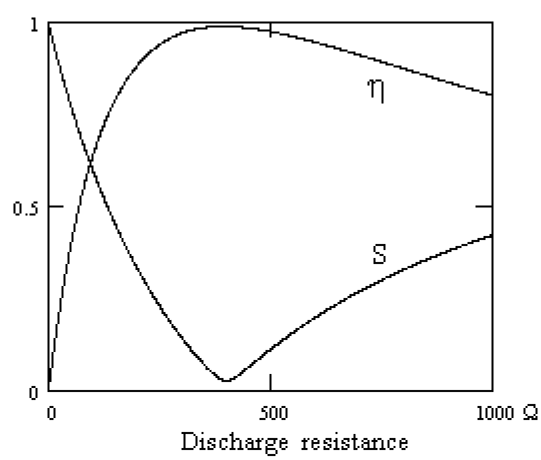
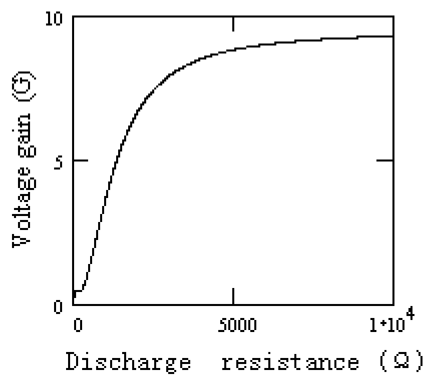


Figure (2): Voltage reflection coefficient (S) and matching efficiency vs discharge resistance (f =120 MHz, C = 9 PF)

To explore the advantage of the matching circuit for laser operation, let us consider the change of discharge resistance and their impact on power transfer from the initial point, when RF power is applied to the circuit. Before gas breakdown, the discharge resistance is effectively infinite, but the voltage gain is very high figure 3, so that discharge initiation can be accomplished. Following breakdown when RF power is dissipated in the ionized gas, the discharge resistance falls rapidly. As the discharge resistance approaches its stable value, the reflection coefficient become smaller and smaller, when more and more power being transferred to the gas discharge matched condition is achieved and maximum power is transferred from the supply to the laser head figure 2.



Figure(3): Voltage gain (G) vs discharge resistance(f =120 MHz, C = 9 PF)

At this point, if the discharge resistance decreases further, say as a result of fluctuation in the power supply, the gain of the matching circuit will fall and more power be rejected .As a result, the discharge resistance will be forced to rise again towards the equilibrium position.

Conclusion:

The problem of two channels breaking down simultaneously, two key measures were taken. First is the uniform voltage distribution along the two channels, second is the optimized matching circuit (equivalent circuit of Γ matching network) between the generator and the laser head. Expressions for power transfer coefficient and voltage gain have been derived and the required value of matching circuit components indicated. These have been interpreted and discussed for a range of condition relevant to the operation of RF discharge excited partial Z-fold waveguide CO_2 laser.

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دراسة توافق الممانعه في التردد الراديوي لليزر ثاني أوكسيد الكاربون ذو الموجه الموجهه المتهيج والمطوي على شكل حرفZ

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الخلاصه:
شبكه توافق للدائره المكافئه من نوع Γ قد طبقت لقياس ممانعة ليزر ثاني اوكسيد الكاربون ذو الموجه الموجه المتهيج والمطوي جزئيا على شكل حرف بالاضافه الى ذلك نوقشت شروط التصميم لأختيار محاثة الملف وخواص رأس الليزر للحصول على أفضل تحول للقدره.