TE_{10}^{R} – TE_{11}^{C} Input Coupler for a Low-THz Gyro-TWA

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***Abstract*— The design of a fundamental rectangular-to-circular coaxial cavity input coupler for a low-THz gyro-traveling wave amplifier (TWA) is presented. Theoretical and numerical approaches to the design of the coaxial cavity input coupler are introduced. The design is optimized for operation between 360 – 384 GHz, achieving a transmission bandwidth of 7.5% (358 – 386 GHz). A comment on the manufacturability of sub-mm waveguide channels is included.**

Keywords—input coupler; mode coupling; gyro-TWA.

I. INTRODUCTION

A gyro-travelling wave amplifier (gyro-TWA) is a broadband amplifier of coherent electromagnetic (EM) radiation. The cyclotron resonance maser (CRM) instability, a beam-wave coupling mechanism, drives a convective instability within the gyro-TWA interaction circuit resulting in growth of an input EM wave. The instantaneous bandwidth of a gyro-TWA lends the vacuum device to applications including radar systems [1], communications [2] and plasma heating [3].

A low-THz gyro-TWA is being developed at the University of Strathclyde with a view to applying the vacuum design in the dynamic nuclear polarization (DNP) enhancement of a nuclear magnetic resonance (NMR) imaging system. The use of a high power gyro-TWA in a DNP-NMR imager will increase the radiation power delivered to the sample and, hence, greatly improve the sensitivity of the NMR experimental results.

The design of a 372 GHz gyro-TWA is currently under investigation. The device uses a cusp electron beam [4 - 5] to deliver power in the 10’s – 100’s W range with a target frequency bandwidth of ~7% and a saturated gain of 40dB. Broad knowledge of gyro-device development gathered at the University of Strathclyde will be applied in the design of the amplifier with extensive research on the active and passive components required for gyro-device operation having already been carried out [6-9].

The unique helically corrugated interaction waveguide (HCIW) [10] couples the TE_{21} mode to spatial harmonics of the TE_{11} mode, generating an operating eigenwave. The eigenwave group velocity, v_g, is constant over a broad bandwidth; hence no change to the magnetic field is required to achieve synchronous interaction between the electron beam and the eigenwave. Therefore, a gyro-TWA operates over a broad bandwidth without tuning the magnetic field. Fig. 1 highlights the dispersion in a helically corrugated cavity.

Efficient coupling of the desired mode into the interaction cavity is vitally important to the performance of a gyro-TWA. High gain will not be achieved if extensive radiated power is lost at the input coupler. The design and optimization of a coaxial cavity input coupler, coupling from the TE_{10}^{R} mode to the TE_{11}^{C} mode, is discussed. The superscripts ‘R’ and ‘C’ denote the transition from rectangular to circular waveguide. The operation of the input coupler is defined by the transmission level being above – 1dB, with the deviation about the center frequency defining the bandwidth. The theoretical and numerical design of the coaxial cavity coupler is shown and a comment on the manufacturability of the device at low-THz frequencies is made.

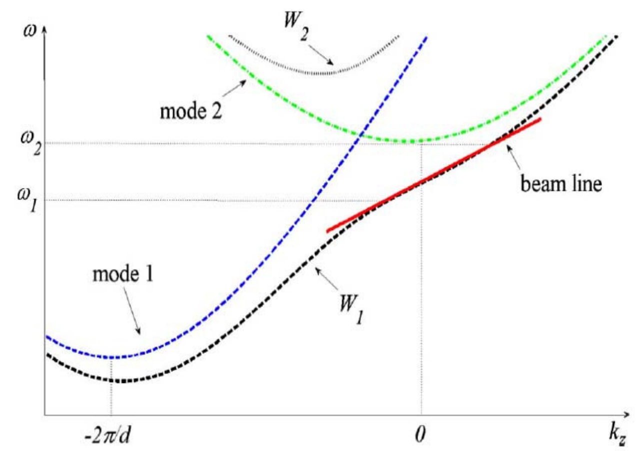

Fig. 1: Dispersion of the HCIW with W_1 – operating eigenwave, mode 1 – TE_{11} dispersion, mode 2 – TE_{21} dispersion, W_2 - spurious eigenwave and intersecting electron beam dispersion.

II. COAXIAL INPUT COUPLER DESIGN

A coaxial input coupler, shown in Fig. 2, is a 3-port structure which can be designed to convert the fundamental mode in a rectangular feed waveguide to the fundamental TE_{11} mode or higher order modes in a circular waveguide with a high degree of mode purity. Coaxial cavity input couplers have been designed to propagate radiation into the cavity structures of gyroklystron amplifiers [11-12] and as the input section of UC Davis’ (UCD) W-band gyro-TWA [13]. The coaxial cavity TE_{01} input coupler, utilised on the gyroklystron, achieves an operating bandwidth of ~3% with a centre frequency of ~35 GHz whereas the broadband UCD TE_{01} coupler operates about a centre frequency of ~96 GHz with a bandwidth of 7 GHz (~7%). Therefore, careful design of the coaxial input coupler will ensure it can be applied to a gyro-TWA with a target bandwidth of ~5%. The design of a fundamental rectangular mode to fundamental circular mode coupler, centred at 372 GHz, is presented in a bid to analyse the potential application of a coaxial cavity coupler to a low-THz gyro-TWA.

The coaxial coupling structure, shown above, consists of a rectangular input waveguide of width (*a*) and height (*b*) coupled to a coaxial cavity of width (*d*) and thickness (*t*). The interface between the coax cavity and the rectangular guide is,

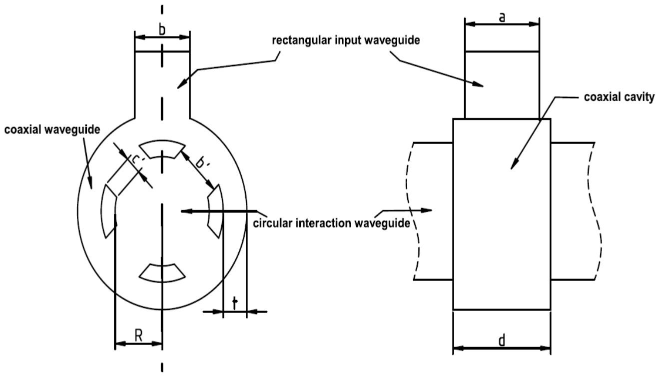

Fig. 2: Schematic of a coaxial cavity coupler with (L) front view and (R) side view.

in essence, a waveguide T-junction if $b \approx t$. The coax cavity couples into the circular interaction waveguide, of radius (R), through a series of apertures of width (a'), height (b') and length (c'). Careful placement of the apertures around the interaction guide centre can lead to the excitation of high order TE_{mn} and TM_{pq} modes, with the generated mode dependent on the orientation of the apertures. For example, the generation of TE_{m1} modes can be achieved by placing $2*m$ apertures at nulls of the electric field in the interaction cavity, spaced equally around the circular waveguide. The apertures can be modelled as dipole radiators allowing for the scattering matrix at the interface between the coax cavity and the interaction waveguide to be generated. This can, in turn, be solved alongside the scattering matrix of the waveguide T-junction to allow for a numerical description of the coupling.

Reference to [11] was made throughout the design of the coaxial input coupler with key points highlighted. The field in the coaxial waveguide develops upon interaction with each rectangular aperture. The field amplitude at the i-th aperture is given by

$$A_i^{\pm} = exp\left(\mp\gamma\varphi_i A_{0i}^{\pm}\right) \quad (1)$$

where $\gamma = \alpha + j\beta$, α is the attenuation constant of the wave in the cavity region, β is the azimuthal phase constant, +/- indicates a forward/backward propagating wave respectively, φ_i is the angle of the i-th aperture from the input guide/coaxial cavity interface and $A_{0i}^{\pm}$ is the incident field amplitude. $A_{0i}^{\pm}$ is dependent on the radiated electric (P_i) and magnetic (M_i) field from the previous dipole aperture with the magnetic dipole field split into azimuthal and axial components. The incident field amplitude at the i-th aperture can be written as

$$A_{0i}^{\pm} = exp(\pm\gamma\varphi_i)\left[M_i^{\varphi}\mathfrak{K}_i \pm M_i^{z}\mathfrak{N}_i + P_i^{r}\mathfrak{I}_i\right] \quad (2)$$

The components associated with the azimuthal magnetic dipole field (M_i^{φ}), axial magnetic dipole field (M_i^{z}) and the radial electric dipole field (P_i^{r}) can be found in [11]. For strong coupling, the axial magnetic dipole field should be made as strong as possible. M_i^{z} increases with axial aperture length suggesting that oval-shaped or rectangular apertures will increase the coupling coefficient. Increases in the azimuthal width of the slot aperture (b') will result in a nominal increase in coupling; however, this will also cause degradation to the mode purity in the interaction waveguide.

A $TE_{10} – TE_{11}$ input coupler is designed using CST MWS

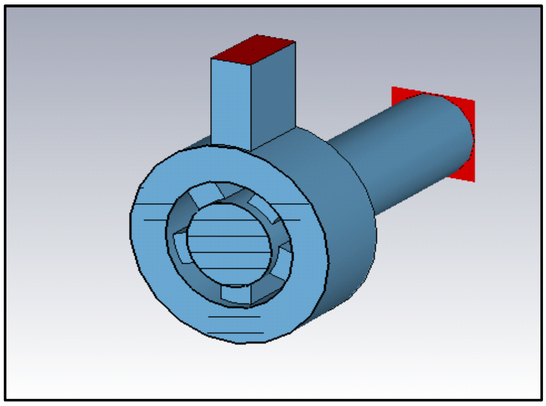

Fig. 3: MWS representation of sub-mm wave coaxial input coupler.

(Fig. 3). The interaction waveguide radius is determined by limitations imposed by the gyro-TWA system, with R = 0.350 mm. The waveguide width (a) is set at 0.650 mm with a width-to-height ($a : b$) ratio of 1 : 2. To ensure the waveguide T-junction approximation made in the theory is applicable to the input coupler, the cavity width (d) is initially set equal to a and, for all evaluations, $d \approx a$. Due to the TE_{11} field profile in the interaction waveguide, placement of the slot apertures is dependent on coupling strength as opposed to generating the required distribution of the E-field in the circular waveguide.

Rectangular apertures, opposed to oval-shaped apertures, are chosen to ensure a high M_i^{z}-component and to aid in the manufacturability of the coupler. The aperture width (a') is set equal to the waveguide width before parametric optimisation is carried out. An aperture azimuthal width-to-height ($a' : b'$) ratio of 1 : 2 is employed. The aperture length (c') is set to be much less than the guide wavelength in the rectangular waveguide ($c' \ll \lambda_g^R$) to allow for the dipole assumption made in the theory to be applicable. The guide wavelength in a rectangular waveguide is calculated using

$$\lambda_g^R = \frac{c}{f} \times \frac{1}{\sqrt{1 - \left(\frac{c}{2af}\right)^2}} \quad (3)$$

where f is the centre frequency in the operating band.

The structure is designed in the numerical software as shown in Fig. 3. A waveguide of radius R is employed at the output of Port 2 and Port 3. Therefore, the electromagnetic radiation is equally as likely to propagate from either port with a maximum achievable coupling strength of -3 dB. The initial model construction is used to minimize the reflection at the rectangular port (Port 1). The numerical modelling displayed a reflection of < -10 dB at Port 1 between 360 – 384 GHz with a and b set at 0.650 mm and 0.325 mm respectively. The reflection coefficient could not be improved with changes to the waveguide dimensions. The optimized coaxial width (d), coaxial thickness (t) and aperture parameters (a', b' and c') are shown in Table I.

Equal transmission of input radiation is not acceptable for a gyro-TWA input coupler. The coupler must terminate the propagation of the input signal towards the diode region of the vacuum device (Port 3). The use of a cut-off waveguide reflector at Port 3 is a general solution to prevent the propagation of significant levels of radiation into the electron gun. A lower frequencies (Ka band and below), a waveguide reflector is a simple, practical method of frequency selective

TABLE I: COAXIAL CAVITY WAVEGUIDE PARAMETERS.

Parameter	Magnitude (mm)
a’	0.540
b’	0.300
c’	0.210
d	0.750
t	0.300

feedback. However, at low-THz frequencies, a step-down reflector can cause a hindrance to the electron beam transportation and, hence, limit the electronic efficiency of the device. Therefore, it is beneficial to increase the diameter of the tunnel through which the electron beam may propagate whilst hindering the transport of oncoming radiation.

A Bragg reflector [14] is a waveguide structure with radial periodicity which can be used as a method of providing frequency selective feedback. A review of a Bragg reflector design in the W-band is presented in [15]. The design process was applied and an optimized reflection of ~100% in the desired frequency band was achieved for the condition that the radii of the reflector sections are larger than *R*.

The determined parameters for the optimized coaxial cavity structure (Table I) are simulated with an attached Bragg reflector. The numerical scattering of the optimized coaxial cavity input coupler is shown in Fig. 4.

The coaxial cavity $TE_{10}^{R} - TE_{11}^{C}$ coupler achieves a -1 dB coupling with a bandwidth of 7.5% covering the proposed operating range of 360 – 384 GHz for the low-THz gyro-TWA. The Bragg reflector attached to the coaxial cavity coupling structure is effective at preventing the propagation of radiation towards the electron gun with < 10% of the input power propagated into the diode region. In a practical application, this is low enough to prevent disturbances to the field profile between the cathode and anode and the electron beam transportation is unaffected. Therefore, if this coupler were to be manufactured for the amplifier system a Bragg reflector structure would be implemented at the input coupler.

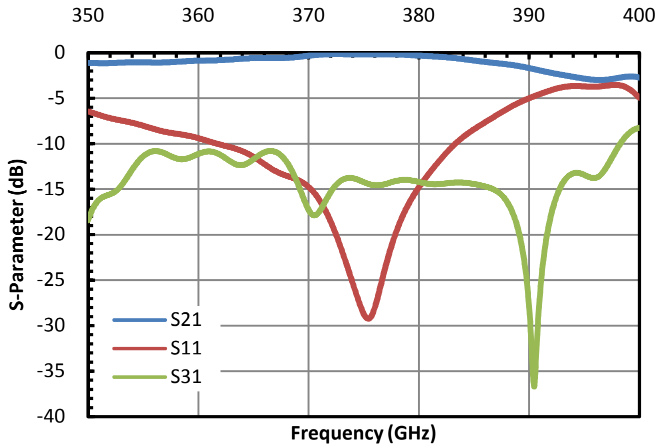

Fig. 4: Simulated transmission and reflection of coaxial cavity input coupler.

III. MANUFACTURABILITY

The manufacturing of low-THz waveguide components is challenging; however, with modern computer numerically controlled (CNC) machining it is possible construct waveguide channels of sub-mm dimensions. High level CNC milling machines can achieve a positional tolerance of ±1 μm [16]. Therefore it is possible to control the manufacture, from the dimensions in Table I, to ensure that the passive input coupler waveguide channels will operate between 360 – 384 GHz. A CAD drawing of the coaxial channel machined into a metal plate is shown in Fig. 5. Two identical plates would be constructed and joined together to form the complete coaxial waveguide.

The Bragg reflector structure would be manufactured using a metal former which, again, utilizes the CNC milling technique to construct the periodic steps of the circular cross-section component. The machining tool can be designed to match the period length of each Bragg step to ensure the former is as close to the modelled parameters as possible. A copper growing technique would then be applied to the former mandrel, with the metal former subsequently dissolved. The copper structure would, as a result, form the Bragg reflector which would be attached to the coaxial waveguide structure.

The CNC milling technique has been employed to manufacture a 385 – 500 GHz orthomode transducer (OMT), used to split incoming signals in a radio-astronomy receiver [17]. The un-plated copper blocks were fabricated at the University of Arizona using a state-of-the-art milling machine. The scale of the waveguide channel machining is shown in Fig. 6, highlighting waveguide channels of 72 μm width. Hence, the design parameters documented in Table I for the 360 – 384 GHz coaxial input coupler would be readily achievable on a high level micro-milling machine.

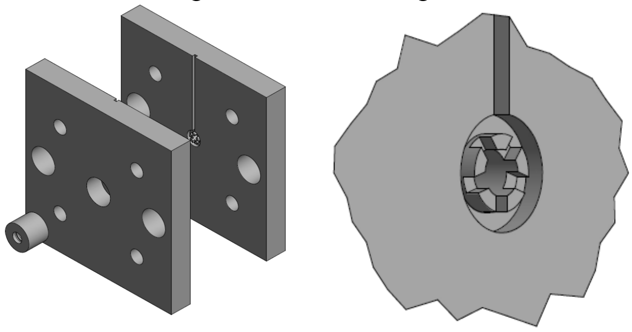

Fig. 5: CAD drawing of coaxial input coupler; (L) the complete coupler with Bragg reflector and (R) close up of waveguide channel.

IV. CONCLUSION

The design on a fundamental mode rectangular-to-circular coaxial waveguide input coupler has been presented. The $TE_{10}^{R} - TE_{11}^{C}$ coaxial coupler operates at the gyro-TWA frequency range of 360 – 384 GHz with an achieved a bandwidth of 7.5%. The implementation of a Bragg reflector has ensured that beam transport is unhindered whilst preventing electric field disturbances in the diode region of the amplifier with < -10 dB of input radiation transmitted to the electron gun. A discussion on manufacture was presented, highlighting the sub-mm waveguide dimensions achievable with state-of-the-art CNC micro-machining. Therefore, it is possible to manufacture the coaxial input coupler waveguide parameters used in the modelling of the coupling structure.

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