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Operation of a 140 GHz Gyro-amplifier using a Dielectric-loaded, Sever-less Confocal Waveguide

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Abstract

The design and experimental results of a 140 GHz gyro-amplifier that uses a dielectric-loaded, sever-less confocal waveguide are presented. The gyro-traveling wave amplifier uses the HE_{06} mode of a confocal geometry with power coupled in and out of the structure with Vlasov-type, quasi-optical couplers. Dielectric loading attached to the side of the confocal structure suppresses unwanted modes allowing zero-drive stable operation at 48 kV and 3A of beam current. The confocal gyro-amplifier demonstrated a peak circuit gain of 35 dB, a bandwidth of 1.2 GHz and a peak output power of 550 W at 140.0 GHz.

I. Introduction

There is an active interest in designing high-gain amplifiers for use with dynamic-nuclear-polarization-enhanced nuclear magnetic resonance (DNP/NMR). Currently, gyrotron oscillators at frequencies of 140, 250, 330, and 460 GHz are in operation at the Francis Bitter Magnet Lab at MIT [1–7]. These DNP/NMR systems all use continuous wave (CW) sources. The polarization enhancement in CW DNP/NMR spectroscopy scales inversely with increasing magnetic field. This means that as NMR proceeds towards higher magnetic fields the enhancement is adversely affected. Pulsed DNP/NMR can help with maintaining a strong signal enhancement at high magnetic field strengths [8]. Previously, pulsed DNP has been achieved using an IMPATT diode driver [9, 10]. The pulse length of 50 ns at 35 mW and 140 GHz was able to excite 1% of the sample's linewidth [9]. In order to capture the entire linewidth, a shorter and more powerful pulse is needed, on the order of 100 W to 1 kW at 1 to 10 ns, assuming a cavity Q of several hundred [11, 12]. For pulsed DNP/NMR, gyro-amplifiers are a good candidate for generation of the required pulses. Additionally, the frequency scaling of gyro-amplifiers is a useful feature for accessing various frequencies. To date, amplification of short pulses has been demonstrated at 140 GHz [13], and at 250 GHz [14,15].

Contemporary gyro-amplifiers take advantage of a variety of design approaches [16]. Lossy-wall gyro-amplifiers have been designed and operated at 35 GHz [17, 18] and at 95 GHz [19]. As the gyrotron frequency increases, it is advantageous for the gyrotron amplifier to operate in a higher order mode of the interaction circuit to minimize space charge effects and ohmic loss. One possible design feature is a helically-corrugated interaction circuit [20,21]. We present a confocal interaction circuit as an alternative to lossy-wall designs. The

confocal waveguide structure is a candidate for an interaction circuit geometry that can reduce mode competition [22, 23]. Gyrotron devices with confocal circuits continue to be studied intensively [24–28].

II. Principles of Operation

The gyro-amplifier works by transferring the energy associated with the perpendicular velocity of a gyrating, mildly relativistic electron beam to the field of a microwave pulse. The microwave field is confined in the transverse electric mode of a waveguide. The gyration of the electron beam is supported by a magnetic field. The dispersion relations for the waveguide mode and the electron beam may be written as follows:

$$\omega^2 - k_z^2 c^2 - k_\perp^2 c^2 = 0 \quad (1)$$

$$\omega - \Omega/\gamma - k_z v_z \geq 0 \quad (2)$$

where k_z and $k_\perp$ are the components of the wavevector, ω is the angular frequency, $\Omega = eB_0/m_e$ is the cyclotron frequency, and γ is the relativistic factor. In Ω , e is the electron charge, B_0 is the magnetic field, m_e is the electron mass. We note that the dispersion relations experimentally depend on the magnetic field, the beam voltage, and the pitch factor $\alpha = v_\perp/v_z$ (in which $v_\perp$ and v_z are the perpendicular and axial velocity components of the electron beam, respectively). Gain occurs when the dispersion curves described by Eqs. 1 and 2 are near intersection. This can be shown visually in Fig. 1. The ability to experimentally tune laboratory parameters such as beam voltage and magnetic field, as well as the choice of a waveguide cutoff by mechanical design, allow the possibility to engineer an interaction circuit to amplify at a desired frequency range. The confocal geometry is a choice of interaction circuit that supports transverse electric modes and is amenable to the gyro-amplifier setup.

The confocal geometry is defined as a set of two curved mirrors with radius of curvature R_c equal to their separation distance, $L_\perp$ ($R_c = L_\perp$). This geometry is shown in Fig. 2. The total width of each mirror, known as the aperture, is $2a$. This width can be adjusted to either increase or decrease the diffractive losses experienced by the supported modes of this open geometry, which are the HE_{mn} modes. The mode numbers m and n denote the spatial variations in the $\hat{x}$ and $\hat{y}$ directions, respectively. The example in Fig. 2 shows the HE_{06} mode, as indicated by the six variations in the $\hat{y}$ direction.

For a mirror radius of curvature $R_c = 6.83$ mm, 140 GHz radiation is supported by the HE_{06} mode. The dashed line in Fig. 2 shows the annular electron beam of radius $R_b = 1.8$ mm, which is seen to interact with the second and fifth peaks of the HE_{06} mode. As stated previously, the open geometry of the confocal interaction circuit allows for radiative losses. This mechanism is directly responsible for the mode selectivity of the system, as lower-order modes feature a high attenuation per unit distance along the axial dimension of the circuit.

Figure 3 shows a comparison of the HE_{06} and HE_{15} modes; the transverse extent (“footprint”) of the two modes is seen to be different. In particular, the broader extent of the HE_{15} mode in the $\hat{x}$ direction is the reason for the attenuation per unit distance being higher than for the operating mode HE_{06} .

An additional feature of the confocal circuit is that the absence of lossy materials allows for, in principle, a continuous wave operation. Diffractive loss, as opposed to lossy materials, avoids the heating that would prevent continuous wave operation. The present experiments, however, were all conducted with 2 microsecond pulses.

III. Gyro-amplifier Experimental Setup

The 140 GHz gyro-amplifier experiment is centered around a 6.2 T Magnex Scientific magnet, which has a $\pm 1\%$ flat field of 20 cm. Shielding in the magnet design causes the axial magnetic field B_0 to fall off as z^{-4} near the electron gun’s cathode. A 12.7 mm diameter corrugated waveguide acts as a transmission line that brings power from the RF input drive sources. A cutaway view of the 1.5 m, 11.4 cm diameter stainless steel gyro-amplifier tube is shown in Fig. 4.

As part of the setup to transport microwave power to the circuit, individual sections of 20 cm corrugated waveguide were manufactured. These were clamped together to create a length of corrugated waveguide over 2.5 m in length. Microwaves are introduced into the vacuum chamber through a 3.28 mm Corning 7940 fused quartz window. This extensive input transmission line setup introduces a loss to the transported microwave power, which in the frequency range of interest (137 to 143 GHz) is about 6 dB in total.

It is important that the mechanical and magnetic field axes are aligned because a misalignment would result in the electron beam missing the interaction with the confocal mode. The meter-long system that supports the confocal circuit as well as the input and output corrugated waveguide is inserted horizontally into the vacuum tube and is secured by a taper and clamp arrangement. In order to maintain a straight alignment to the vacuum tube mechanical axis, this meter-long system is supported by stainless steel bracers that are compressed with a spring washer when the tube is assembled.

The interaction circuit is a 20 cm set of copper rails arranged with the confocal geometry described. Their radius of curvature, equal to their separation, is 6.83 mm. The aperture ($2a$) of these rails is 4.3 mm, which at 140 GHz provides about 4 dB/cm of attenuation due to diffractive losses. A cutaway schematic showing the detailed arrangement of the confocal rails along with the reciprocal input/output mode converters is shown in Fig. 5

The electron gun used is a CPI triode configuration, non-laminar VUW-8140 MIG gun, with nominal operating parameters of 65 kV and 5.0 A of beam current. These conditions were designed to operate at 5.6 T to produce a pitch factor a of 1.5 and a perpendicular velocity spread of 2.7%. For use as a gyro-amplifier at 140 GHz, the gun was ultimately run at a different operating point of 5.087 T, 48 kV beam voltage, 34 kV mod-anode voltage, a pitch factor of 0.64, and beam current up to 3 A.

The small signal gain of the gyro-amplifier is studied by using a solid state RF driver as an input source to the system. This Virginia Diodes amplifier multiplier chain (AMC) has an output power of about 50 mW over a bandwidth of 138 to 144 GHz. The AMC is able to function as either a continuous wave or as a pulsed source. Saturated gain behavior is studied by using an extended interaction oscillator manufactured by CPI. This source is operated in a pulsed capacity with a pulse width of 2 microseconds over a tunable band of 139.5 to 142 GHz. The output power into the transmission line is about 50 W at its peak and may be varied with an attenuator.

IV. Mode Converter Cold Test

The gyro-amplifier experiment features a 12.7 mm diameter corrugated waveguide for transmitting RF power into the vacuum tube. It is necessary to couple power from the HE_{11} mode of the corrugated waveguide into the HE_{06} mode of the confocal circuit. This is accomplished by using a quasi-optical mode converter with a Vlasov-style design [29]. A scale model of the Vlasov-style mode converter, shown as a cutaway CAD figure in Fig. 6, was fabricated and cold tested using a vector network analyzer (VNA). The scale model is identical to the complete structure except that the length of the confocal rails is 3 cm versus 20 cm in the full structure.

The scale cold test model mode converter was fully simulated with the commercial software CST Microwave Studio. A comparison of both the measured (VNA) and simulated (CST) S_{21} parameters is shown in Fig. 7. The S_{21} parameter shown is for the entire scale model, calibrated at the waveguide input to the quasi-optical launcher, and therefore includes the losses from both sets of launchers. Good agreement between simulation and measurement indicates a successful fabrication of a quasi-optical mode converter for the confocal HE_{06} mode.

The quasi-optical design furthermore reduces backward reflections in the corrugated transmission line as it avoids the downtaper that a fundamental waveguide WR8 input section would require. Additionally, the integrated parabolic mirrors, cut from the same copper section that forms a confocal rail, helps to ensure the inline mechanical alignment of the confocal circuit.

V. Suppression of Vacuum Pipe Modes

Numerical studies performed in CST Microwave Studio showed that the interior wall of the vacuum chamber that houses the confocal circuit supported vacuum pipe modes that coupled back into the interaction region of the confocal geometry. In order to suppress these vacuum pipe modes, the dielectric ceramic Macor was added into the vacuum tube on the flanks of the confocal structure. Fig. 8 shows the computed spatial mode pattern for a 126.5 GHz eigenmode of the entire cross section of the vacuum tube, including the vacuum tube inner walls and the confocal structure, with and without the inclusion of the Macor dielectric.

The addition of Macor bars creates an absorptive loss, which supplements the diffractive loss mechanism of the confocal geometry. A Q factor was computed by CST Microwave Studio for the vacuum pipe modes with and without the Macor bars. As shown in Table I, the

Macor bars significantly dampen the quality factor of the vacuum pipe modes and help to prevent these parasitic oscillations at unwanted frequencies.

The inclusion of these Macor bars led to zero-drive stable operation at beam currents above 2 A and operating voltages above 30 kV. This is a requirement for successful amplifier operation at 140 GHz and for application to DNP NMR systems.

VI. Experimental Results

The application to DNP/NMR sets the experimental design goals, which are shown in Table II. These values allow coherent excitation of the sample linewidth [11,12].

Losses in the gyro-amplifier system mean that the actual confocal circuit interaction needs to produce a high gain in order to achieve a high power for small signal amplification. The main sources of loss are the transmission waveguide and window setup as well as the reciprocal input/output quasi-optical mode converters. At 140 GHz, the total loss due to the sum of input and output coupling is about 12 dB, which is the offset when comparing device and circuit gain, the latter of which may be predicted using numerical simulations.

The numerical code MAGY was used to simulate gain in the confocal circuit [30]. At 5.08 T, 46 kV, 3 A of beam current and a pitch factor α of 0.8, a circuit gain of about 50 dB is predicted, provided that perpendicular velocity spread is low at 3%. Figure 9 shows the effect of an increase in perpendicular velocity spread from 3 to 5%. A drop in the simulated peak circuit gain from 50 to 40 dB due to an increase in the velocity spread illustrates the sensitivity of amplifiers to electron beam quality.

During initial hot tests of the gyro-amplifier, parasitic oscillations in the range of 126.5 GHz were observed at operating voltages around 45 kV and beam current of 1 A. In order to achieve high gain, operation around this voltage and a higher current of 3 A are desirable. The addition of Macor bars allowed for zero-drive stable operation at the target voltage and beam current, in which the parasitic oscillations were suppressed by the mechanism described in Section V. The electron gun code MICHELLE calculates a pitch factor α of 0.60 at the design operating point at 5.08 T. The experimental data and numerical calculation are shown in Fig. 10 for the operating point of 5.08 T, 46 kV, 3 A, and α of 0.60. The peak gain is measured at 139.4 GHz and is about 35 dB of circuit gain or 23 dB device gain. Agreement between experiment and numerical simulation using MAGY is achieved when perpendicular velocity spread is at 6%.

The results in Fig. 10 were optimized for 139.4 GHz. For optimization at 140.0 GHz, the operating point was adjusted slightly to 5.087 T, 48 kV, and 3A of beam current. At this operating point, a peak circuit gain of about 35 dB (or 23 dB device gain) was measured at 140 GHz with a 3 dB bandwidth of 1.2 GHz. This measured gain bandwidth is shown in Fig. 11. At this operating point, the numerical electron gun code MICHELLE predicts a pitch factor α of 0.64. Given a perpendicular velocity spread of 6%, MAGY predicts a good agreement with the measured gain.

The saturated gain characteristics of this high gain operating point were also explored. Figure 12 shows a comparison of measured to simulated saturated gain behavior. At the high gain operating point the output saturated power reaches about 550 W at 140.0 GHz.

VII. Discussion and Conclusion

Using a newly designed set of reciprocal input/output quasi-optical mode converters, the confocal gyro-amplifier has demonstrated a peak circuit gain of 35 dB at 140 GHz with a bandwidth of 1.2 GHz. At this same operating point, the saturated output power at 140 GHz was measured at about 550 W. The measurements were performed under zero-drive stable conditions, necessary for application to DNP/NMR. Vacuum pipe modes were identified and simulated successfully using CST Microwave Studio. The inclusion of dielectric Macor bars in the vacuum tube reduced parasitic oscillations, which enabled this zero-drive stability. Following the successful demonstration of zero-drive stable, high power operation, research will now commence on pulsed DNP/NMR experiments at MIT.

The efficiency of the gyro-TWT is limited by the large number $N(= 270)$ of gyro-orbits along the 20 cm interaction space. In the case of no velocity spread, simple estimates of the amplifier efficiency predict about 4% [16,31]. This efficiency agrees well with our MAGY calculations for a lossless circuit with no velocity spread. The observed reduced efficiency of $\sim 0.4\%$ arises primarily from velocity spread.

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Fig. 1.

The dispersion curves, given by Eq. 1, are plotted for three modes (HE_{06} , HE_{15} , HE_{05}) of a confocal waveguide. Also plotted is the electron beam line given by Eq. 2. The parameters of the plot are typical for the present experiments with $B_0 = 5.087$ T, beam voltage of 48 kV, pitch factor $\alpha = 0.64$, and confocal rail spacing of 6.83 mm. The electron dispersion line is tangential to the waveguide mode curve around 140 GHz. The intersection of the electron beam line with the backward wave curves of the HE_{15} and HE_{05} modes indicates a potential source of parasitic oscillations that need to be suppressed.

Fig. 2.
The confocal geometry including the field distribution of the HE_{06} mode. The dashed line represents the annular electron beam.

Fig. 3.

Contours of the horizontal component of the electric field distribution for the HE_{06} mode at 140 GHz (a) and HE_{15} mode at 126 GHz (b) are plotted. This field distribution is found for an aperture of $2a = 4$ [mm] and $R_c = 6.83$ [mm]. These plots are on a linear scale with yellow showing the highest field values.

Fig. 4.

A cross section schematic of the confocal system setup is shown, in which a) location of electron gun, b) the gun coil magnet, c) confocal circuit, d) input waveguide, e) output waveguide, f) the output window, g) the ion pump, and h) the location of the input window (axis normal to the page). The tube is housed inside of the 6.2 T superconducting magnet.

Fig. 5.

The confocal circuit was fabricated with integral input/output mode converters. The launchers were machined from the same bar of copper that was used to cut the confocal rails, a design feature that improves mechanical alignment.

Fig. 6.
A CAD rendering of the cold test mode converter. This model includes integrated parabolic mirrors that were machined as part of the short confocal rail section.

Fig. 7.

The S_{21} parameter shown for both the measured (VNA) and simulated (CST) results. Good agreement is seen between measurement and numerical simulation.

Fig. 8.

a) 126.5 GHz mode of the entire volume of the vacuum pipe without Macor bars. The vacuum pipe wall supports a mode that has strong fields at the confocal interaction region (located at the center of the simulation and as indicated by the arrows). b) The 126.5 GHz mode is seen to be suppressed by the addition of Macor bars (shown in red). These plots are on a linear scale with red showing the location of the highest E field values.

Fig. 9.

Simulated gain bandwidth results from the numerical code MAGY for the case of two different velocity spreads. A drop in simulated peak circuit gain due to a slight increase in velocity spread demonstrates the importance of good electron beam quality. These simulation results are for an operating point of 5.08 T, 46 kV, 3 A, and $\alpha = 0.8$.

Fig. 10.

Zero-drive stable gain bandwidth is shown as the blue line with a peak of about 35 dB at 139.4 GHz. Good agreement is seen with a MAGY simulation at a velocity spread of 6%. These are the experimental results for the operating point at 5.08 T, 46 kV, 3 A, and $\alpha = 0.60$.

Fig. 11.

Zero-drive stable gain bandwidth is shown as the blue line with a peak of 35 dB at 140.0 GHz. Good agreement is seen with a MAGY simulation at a velocity spread of 6%. These are the experimental results for the operating point at 5.087 T, 48 kV, 3 A, and $\alpha = 0.64$.

Fig. 12.

The measured saturated gain at 140.0 GHz is shown compared to numerical simulation using MAGY. These are the saturation results for the operating point at 5.087 T, 48 kV, 3 A, and $\alpha = 0.64$.

TABLE I

Quality factors computed for several spatial modes of the vacuum pipe.

Frequency	Q no Macor	Q with Macor
126.1 GHz	2.9e4	450
126.2 GHz	4e4	480
126.5 GHz	3e6	170

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TABLE II

Design goals of the 140 GHz confocal gyro-TWT

Frequency	140.0 GHz
Power	> 500 W
Bandwidth	> 1 GHz

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