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Author(s): Moaz M. Altarawneh
Charles H. Mielke
MPA-NHMFL
Los Alamos National Laboratory

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Proximity detector circuits: an attractive alternative to tunnel diode oscillators for contactless measurements in pulsed magnetic fields

M. M. Altarawneh and C. H. Mielke

Los Alamos National Laboratory, MPA-NHMFL, Los Alamos, NM 87545

J. S. Brooks

Department of Physics and National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310, USA

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Abstract

A new radio frequency oscillator circuit based on a proximity detector integrated circuit is described as an alternative for the traditional tunnel diode oscillator used for pulsed magnetic field measurements at low temperatures. The new circuit has been successfully applied to measure the superconducting upper critical field in $Ba_{0.55}K_{0.45}Fe_2As_2$ single crystals up to 60 T. The new circuit design avoids many of the problems associated with tunnel diode circuits while keeping the advantages of contactless measurements in pulsed magnets.

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INTRODUCTION

Radio frequency (rf) contactless measurements are useful to study a wide range of physical properties in materials. In metals, skin depth and sheet resistance are accessible, in superconductors upper critical fields and penetration depths can be determined, and in magnetic materials dynamical susceptibility and magnetic transitions can be measured. Advantages of rf measurements include the high sensitivity (due to high Q, high stability oscillator circuits), and the contactless nature of the measurement. The latter is important for samples that are very small, or have poor contact surfaces, or are air sensitive, or cannot be handled for other reasons, including radioactivity. A mainstay of rf methods in condensed matter has been the tunnel diode oscillator (TDO) since 1975 [1]. The TDO is an rf tank circuit oscillator where the losses in the LC circuit are compensated by biasing the tunnel diode in the negative resistance region ($R_n = (dI/dV)^{-1}$) of its I-V characteristic. See Fig.1 for the tunnel diode I-V characteristic and Fig.2 for an example of a TDO circuitry.

TDO circuits where the sample is placed in the inductor have been successfully used to measure superconducting transitions[3] and the Shubnikov-de Haas (SdH) effect (oscillations in resistivity) as a function of magnetic field in organic conductors in DC field [4] and in pulsed fields [5]. More recently quantum oscillations have been observed using TDO methods in $SrFe_2As_2$[6] and in $YBa_2Cu_4O_8$ [7]. Magnetic transitions in ferromagnetic and antiferromagnetic materials and changes in spin order also have been studied using TDO circuits due to the sensitivity to magnetic transitions [8].

The TDO stability, which can approach $1:10^8$, is perhaps its main advantage. However, there are some significant drawbacks associated with TDO methods. Most problems stem from the narrow range of operating parameters for TDO stability, e.g. the narrow bias voltage range(see Fig.1). Due to the very low operating power of the TDO, the entire circuit is generally placed near the sample coil, and therefore generally in a region of low temperature and high magnetic fields. In cryogenic applications often the optimum parameters allow the TDO to operate only at low temperatures due to the temperature dependent parameters of the TDO characteristics and its circuit components (mainly the tank circuit impedance Z and minimum differential negative resistance R_n). In particular, the impedance of the tank circuit - which is increased as cooling the TDO circuit down - should be equal or slightly larger than the absolute value of the series combination of R_n and R_p (parasitic resistance), in other words, $Z \geq |R_p + R_n|$ [2]. This is particularly acute for applications where small measurement coils are required to increase the filling factor for very small samples(r$\sim$100μm). Likewise, when a sample is changed, it is often necessary to use a different coil to match the sample geometries, and therefore the other parameters need to change as well to stabilize the TDO. In pulsed magnetic fields large induced emf's ($V_{induced}\sim$ 60 mV for 1 mm^2 area) can arise due to un-compensated circuit loops, causing changes in the resonant frequency or driving the TDO out of the stable operating bias condition. (Induced emf's can be reduced[5] by exploiting geometry and compensating coil methods.) Other drawbacks of the TDO technique include the significant cost and lack of availability of the diodes, which are not very robust against failure due to heating during soldering, electrostatic shock, etc. during assembly.

In light of the above, we describe in this short report the application of a very cost-effective and simple alternative to the TDO, namely an inexpensive proximity detector oscillator (or PDO)[9] that removes most of the drawbacks of the TDO circuit, but retains a high stability and sensitivity to changes in materials properties. (In Table I we provide a point-by-point comparison of the two methods.)

THEORY OF OPERATION

In this section, we provide only the essential aspects of TDO-based rf measurements needed to make the TDO - PDO comparison. In a resonant LC tank circuit where $f = 1/2\pi\sqrt{LC}$, a sample (insulated electrically from the tank circuit components) can be inserted into either the inductor or the capacitor. The capacitor mode is generally used for dielectric studies[11], but herein we will focus on inductive sample properties. Changes in skin depth (electrical conductivity) and/or and magnetic moment (magnetic permeability) will alter the inductance of a material in the inductor coil, thereby producing a shift in the resonance frequency, which can be expressed as:

$$\frac{\Delta f}{f_0} = -\frac{\Delta L}{2L}. \tag{1}$$

In practice, all physical parameters of a sample (including dielectric and dissipative effects) will contribute to the shift in frequency, and in many cases the interpretation of Δf can be difficult to interpret beyond the demarkation of a phase transition. (More in-depth treatments of rf measurements are presented in Refs. [2][3][5].)

In superconductors, diamagnetic shielding due to supercurrents is responsible for changing the inductance and frequency of the circuit. These effects are related to the penetration depth of the rf field into the superconductor, and the change in the penetration depth for a cylindrical shaped sample is proportional the change in frequency, expressed as[12]

$$\Delta\lambda = \frac{R^2}{r_s}\frac{\Delta f}{f_0}. \tag{2}$$

where $\Delta\lambda$ is the change in penetration depth, R is the coil radius and r_s is the sample radius.

Hence by changing either the magnetic field or the temperature, the rf circuit will respond significantly upon passing through a superconducting transition in a bulk crystal[13] as long as the filling factor (V_{sample}/V_{coil}) is of the order 0.5 to 1.

APPARATUS

In low temperature condensed matter physics, the pulsed magnetic field experimental environment generally involves a liquid helium cryostat and sample probe to position the sample inside the sensor inductor coil (hereafter L_0) at the center of a pulsed field magnet, where the distance from the sample to the probe top (at room temperature) is typically $\sim$ 1 m. In the standard TDO arrangement the TDO circuit is placed either near the sample and sensing coil at cryogenic temperatures, or at the top of the probe at room temperature (as is the case for the PDO described below and in Fig.3). The inductance of the coax connecting the oscillator circuit to the L_0 sensor coil will be part of the tank circuit. The rf output of the oscillatory circuit (TDO or PDO) is typically down-converted from frequencies in the range 10 to 50 MHz to an intermediate frequency (IF) and the difference frequency is extracted by using a low pass filter at$\sim$2.5 MHz. The IF carrier is recorded with a digitizing oscilloscope over the entire duration of the magnetic pulse. A simple peak-finding algorithm or discrete Fourier transformation is then run on the raw data to calculate the frequency shift Δf (which is generally of order kHz) as a function of time. The time dependent frequency is then correlated with the applied magnetic field yielding the frequency shift vs. magnetic field data (see Fig.5).

In this work we have substituted the TDO circuit (mounted on the top of the probe at room temperature) with the PDO circuit, as shown in Fig.3. The PDO circuit is based on a commercially available integrated circuit (IC) component (TDA0161)[9] normally used for metal detectors. Functionally, the IC works in a manner similar to the tunnel diode in that the effective resistance between pins 3 and 7 is negative, thereby compensating for losses in the effective LC tank circuit between the same pins. The TDA0161 compares the reference resistance between pins 2 and 4 (R_{2-4}) with the effective tank circuit loss R_p, and when the LC circuit is exposed to an external inductive load (e.g. metal object) the change in R_p with respect to (R_{2-4}) induces additional current into pin 1, and this is translated to a metal detector readout. For R_p less than R_{2-4} the circuit will not oscillate. We have modified the IC circuit in the following ways:

1) we have set $R_{2-4} = 0$ with a short so that R_p is always greater than R_{2-4} and the IC will always oscillate.

2) A resistor R_2 was added to maintain a stable operating voltage.

3)The IC operating frequency is available on pin 6, and is read out across the coupling capacitor C_4.

4) The inductor L_1 in the commercial unit (external to the DIP package) is coupled to a secondary coil (L_2) wound around L_1 (air coupled). L_2 is connected in series by coaxial cable to the measurement coil (L_0). The resonance frequency of the PDO depends on the effective inductance of (L_0),(L_1),(L_2) and the connecting coax (effective inductance is given by Eq.3, [10]), which must be within the operating range of the PDO. The total effective inductance can be changed by varying the coupling factor (M). The PDO is optimized to produce a resonance frequency around 10 MHz, but we have successfully operated it up to 28 MHz which make it useful when studying very small samples.

$$L_{eff} = L_1(1 - \frac{M^2}{L_1(L_2 + L_0 + L_{coax})}) \tag{3}$$

The PDO circuit was mounted on a printed circuit board inside a metal box for isolation, and SMA connectors were used for the probe coax and output frequency connections. To compensate for the induced emf in the pulsed field, the design of the sample inductor L_0 involved identical, but oppositely wound coils connected to cancel induced voltages, which is most severe when the field is parallel to the measurement coil axis. Two compensated coil designs are shown in Fig.4, one where identical coils are made separately and then attached, and the other with a continuously wound "figure-8" configuration. (The sample is placed in one of the two coils in a pair see inset I - Fig.5.)

The PDO resonance frequency was stable with a phase noise of less than 50 Hz over ~ 2 hours. The amplitude of the rf oscillations when measured at capacitor C_4 was 100mV.

PDO APPLICATION TO PULSED MAGNETIC FIELD MEASUREMENTS.

The PDO setup was used to study the superconducting state in $Ba_{0.55}K_{0.45}Fe_2As_2$ single crystals and to determine the upper critical field H_{c2} up to 60 T and low temperature of 4.2 K [14]. As it can be seen in Eq.3, when a sample (placed either inside or near the top of the measurement coil) enters the superconducting state, the diamagnetic shielding of the sample decreases the inductance of the measurement coil (L_0) and the effective inductance between pins 3 and 7 causing the resonance frequency to increase. A single crystal of ($0.55 \times 0.55 \times 0.014$ mm^3) was measured in two orthogonal sample orientations: with the applied field normal to the conducting planes (parallel to the crystallographic c-axis) and with the applied field parallel to the conducting planes (perpendicular to the crystallographic $c - axis$. The alignment accuracy in this experiment was within approximately 2°. In the first orientation (B$\|$$c$-axis), the sample was placed on the top of the measurement coil which has a resonance frequency of 28 MHz. In this orientation, a "figure-8" coil (0.7mm diameter each) was needed to cancel out induced voltages that are generated during the field pulse due to the large uncompensated area when a single coil is used (see configuration **I** in Fig.5). In the second orientation (B $\perp$c$-axis$), the sample was placed on the top of a single flat coil (0.8 mm diameter with 5 to 8 turns and 28MHz resonance frequency) laying flat in a plane that is parallel to the pulsed magnetic field, leading to a very small uncompensated area (see configuration **II** Fig.5). In both configurations an increase in the PDO resonance frequency clearly indicated the onset of the superconducting transition at T_c= 32K. Likewise, at lower temperatures as shown in Fig. 5, when the magnetic field approached the upper critical field, the PDO resonant frequency decreased, and from the field dependence of the PDO frequency, the critical field vs. temperature for the material could be obtained[14]. At the critical fields, the shift in resonance frequency Δf for the (B $\|$c$-axis$) orientation is less than that for the (B $\perp$c$-axis$) orientation due to the different filling factor value in each case(filling factor is larger for (B $\perp$c$-axis$) orientation). Nevertheless, the anisotropy and value of the critical fields vs. temperature for both directions are accurately obtained from the data, and the coherence lengths for the different crystallographic directions could be obtained [14].

CONCLUSIONS

The PDO setup has been successfully used as an alternative for the traditional TDO method to carry out measurements in pulsed magnetic fields. The problem of the narrow range operating parameters in the TDO case is avoided by using the PDO circuit which has a wide range of operating parameters(e.g. $V_{operating}$=5 to 35 volt,$I_{operating}$=8 to 12 mA [9]). The wide range operating parameters of the PDO make it insensitive to the pulsed magnetic field whereas the TDO is easily detuned. The PDO chip is relatively robust to heat and electrostatic shock during assembling when compared to the tunnel diode. Finally, the cost of the PDO chip is relatively cheap when compared to the tunnel diodes. Table I summarize the differences between the two methods.

Further improvements on the PDO design would include the availablilty of an IC with a higher operating frequency (above 100 MHz) which would allow the study of smaller samples (i.e. which require smaller L_0 coils), and also to perform experiments on a shorter time scale. For instance, a single turn coil can produce 300 tesla in 6 μS. Finally, the coupling factor between the two inductors L_1 and L_2 could be made tuneable, which would allow the PDO more flexibility for wider inductance range of L_0 and the coaxial connection.

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REFERENCES

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[1] Craig T. Van Degrift *Rev. Sci. Instrum.*, 45: 1171, (1974).

[2] Craig T. Van Degrift, *Rev. Sci. Instrum.*, 46: 599, (1975).

[3] A. Carrington, I. J. Bonalde, R. Prozorov, R. W. Giannetta, A. M. Kini, J. Schlueter, H. H. Wang, U. Geiser and J. M. Williams, Phys. Rev. Lett. **83** , 4172 (1999).

[4] G. J. Athas J. S. Brooks, S. J. Klepper, S. Uji, M. Tokumoto *Rev. Sci. Instrum.*, 64: 3248, (1993).

[5] T. Coffey, Z. Bayindir, J. F. DeCarolis, M. Bennet, G. Esper, and C. C. Agosta, *Rev. Sci. Instrum.*, 71: 4600, (2000).

[6] Suchitra E. Sebastian, J. Gillett, N. Harrison, C. H. Mielke, S. K. Goh, P. H. C. Lau , G. G. Lonzarich, *J. Phys.: Condens. Matter*, 13: 8325, (2001).

[7] E. A. Yelland, J. Singleton, C. H. Mielke, N. Harrison, F. F. Balakirev, B. Dabrowski, and J. R. Cooper *Phys. Rev. Lett.*, 100: 047003, (2008).

[8] M.D. Vannette, A.S. Sefat, S. Jia, S.A. Law, G. Lapertot, S.L. Bud'ko, P.C. Canfield, J. Schmalian, R. Prozorov,*J. Magn. Magn. Mater.*, 320: 354-363, (2008).

[9] ST Microelectronics (www.st.com).

[10] L. Cohen, *Formulae and Tables for the Calculation of Alternating Current Problems* (McGraw-Hill, New York, 1913)

[11] F. M. Ellis, R. B. Hallock and J. S. Brooks, *Rev. Sci. Instrum.* **52** (1981).

[12] C. H. Mielke 1996 PhD Thesis Clark University, Worcester, MA.

[13] E. S. Choi, E. Jobilong, A. Wade, E. Goetz, J. S. Brooks, J. Yamada and M. Tokumoto, *Phys. Rev. B* **67** , 174511/6 (2003).

[14] M. M. Altarawneh, K. Collar,C. H. Mielke,N. Ni, S. L. Bud'ko, and P. C. Canfield , *Phy. Rev. B*, 78: 220505, (2008).

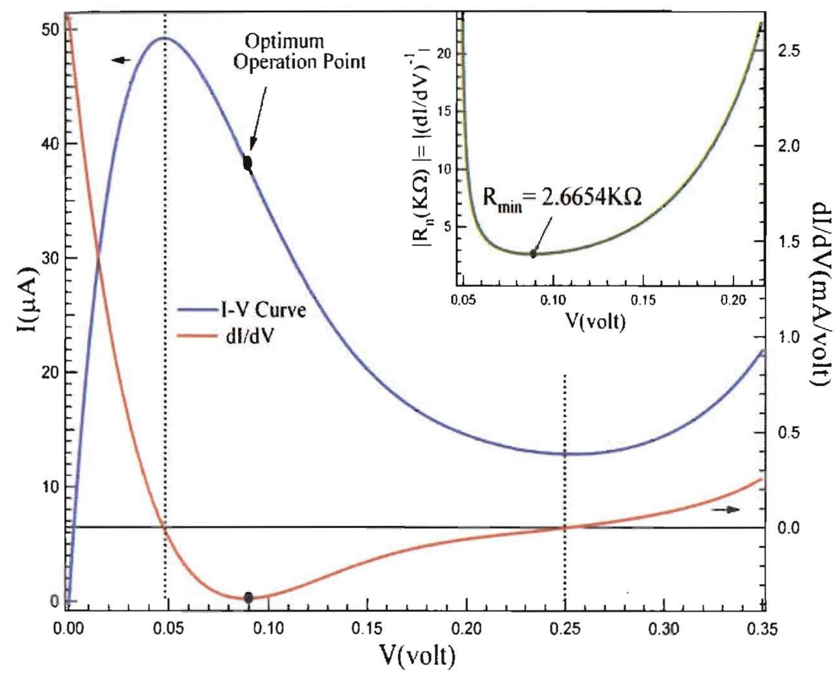

FIG. 1: A BD-5 tunnel diode(manufactured by GPD Optoelectronics Corp) I-V characteristic curve. The vertical dashed lines indicate the possible minimum and maxim operating bias voltage with ΔV=0.2 volt. The inset shows the absolute value of the negative differential resistance as a function of bias voltage.

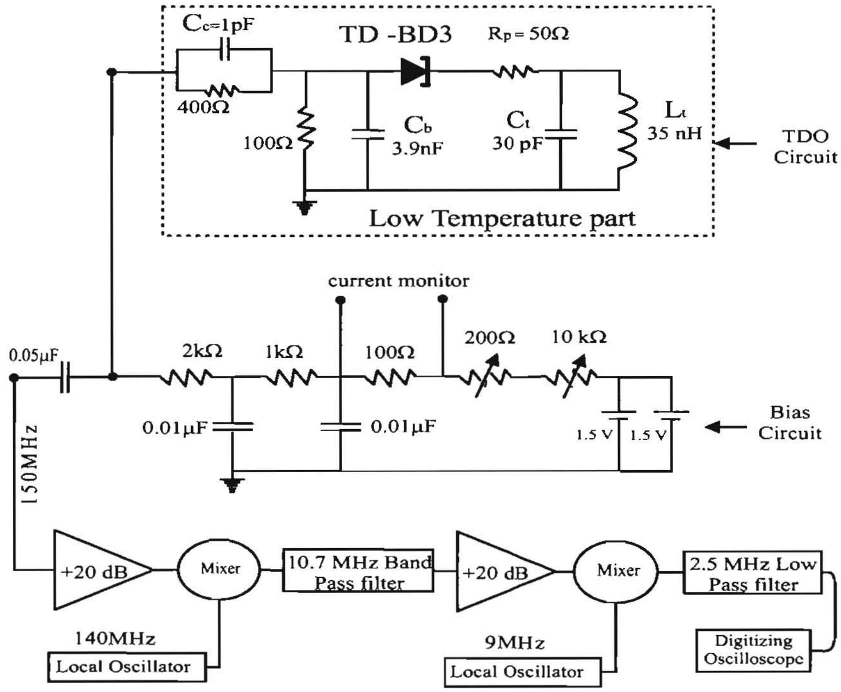

FIG. 2: A schematic diagram of the TDO circuit at low temperature[2], the bias circuit and the signal processing electronics at room temperature. The parameters shown are typical for a BD-3 Tunnel diode(manufactured by Aeroflex-Metelics Corp) operating at 150 MHz.

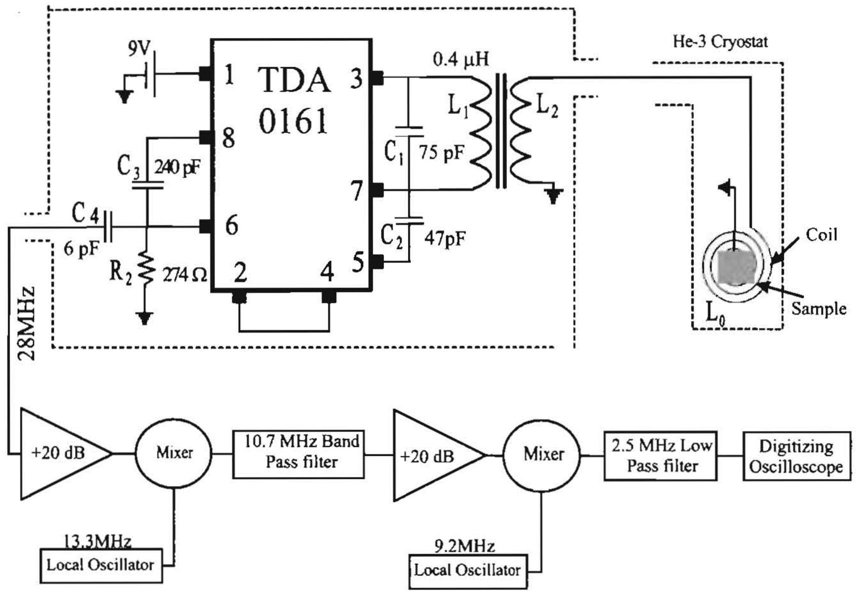

FIG. 3: A schematic diagram of the PDO circuit connected between the measurement coil and the rf signal processing stage. The coupling inductor L_2 and signal inductor L_0 are around 0.2 and 0.017 μH respectively. The contribution from the connecting coax is estimated to be 0.28 μH and C = $92pF$. This circuit operates at 28 MHz.

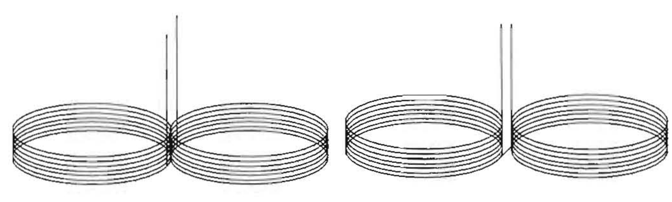

FIG. 4: Figure-8 compensation coil configurations .

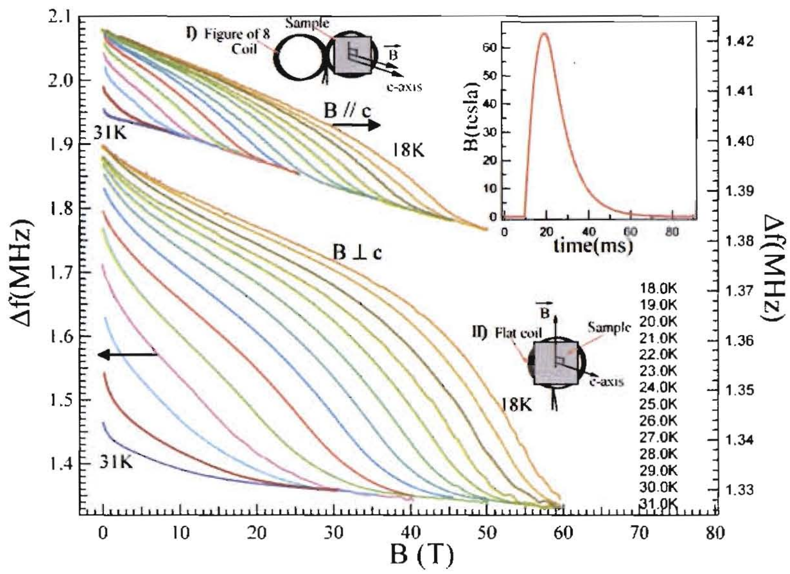

FIG. 5: Critical magnetic field behavior of a single crystal of the anisotropic superconductor $Ba_{0.55}K_{0.45}Fe_2As_2$ at different temperatures from 18 K to 31 K. Left axis: frequency shift as a function of magnetic field applied along the crystallographic c-axis for configuration **I**. Right axis: : frequency shift as a function of magnetic field applied perpendicular to the crystallographic c-axis for configuration **II**). The inset shows the pulsed field profile as a function of time.

	PDO	TDO
Operation	1) The PDO works at room temperature. 2) The PDO uses a 9 volt power supply and no bias tunning is required.	1) The TDO needs to be cooled down to work for small coils, L_0 ~$20nH$. 2)TDO needs a secondary circuit (bias circuit) at room temperature to provide the bias voltage(~100mV) and to separate the rf signal (voltage tunning is required).
Operation in pulsed magnetic field	1) The PDO operation is insensitive to voltages induced by pulsed magnetic fields due to its wide operating voltage range (5 to 35 volt).	1) In pulsed magnetic field environment, the TDO operating voltage (~100mV) is easily detuned from its operating point (V,I) forcing the TDO to stop oscillating.
Performance and stability	1) The PDO provides a very stable frequency with a phase noise less than a 50 Hz when it is modified to produce a 28 MHz. (Phase noise can be less when the PDO is modified to produce 10 MHz for the TDA0161 chip). 2) The drift of the PDO resonance frequency is less than a 100 Hz/hour.	1) TDO Provides very stable frequency with noise phase less than 1 Hz especially when cooled to He-4 temperature. 2) The drift of the TDO resonance frequency can be smaller than a 1Hz in one day under stable thermal conditions[2].
Cost and Availability	1) The PDO chip (TDA0161) is relatively inexpensive (around 2 US dollars at the time of publication). 2) The TDA0161 chip is relatively robust to heating and electrostatic shock during assembly. 3) The TDA0161 chip is widely available.	1) Tunnel diodes are relatively expensive (25 US dollars or more) for high current diodes and more expensive for low current diodes. 2) Tunnel diodes are easily damaged by heat during soldering and electrostatic shock. 3) Few companies now make tunnel diodes due to the low demand.

TABLE I: a comparison between the TDO and the PDO methods.