HIGH POWER X-BAND FERRITE FREQUENCY DOUBLER

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ABSTRACT

This paper describes the development and optimization of an X to K-band frequency doubler. A conversion loss of 3.45 dB was achieved with an input power of 20 kW peak, 12 W average. Efficiency and average power output exceeded previously reported results. The power saturation mechanism is attributed to fundamental processes in the uniform precession mode rather than to spin waves.

Introduction

An efficient lightweight passive device for frequency doubling at high peak power output levels is an attractive means for adding a second operating frequency band to a radar system. Feasibility studies indicated that there were favorable prospects for developing a ferrite frequency doubler similar to the work reported by Vartanian[1], Wiener[2], and others.

Description

The adopted configuration (Figure 1) contains the features described in Wiener's paper. The ferrite was located close to the junction of an X-band guide having an orthogonal K-band waveguide extension. The K-band waveguide broadwall was coplanar with the X-band and the K-band guide was cross-polarized. Step transformers in the X-band guide form a reduced height section which appears as a waveguide below cutoff to the K-band TE_{01} mode. The transformer is designed to have negligible effect on the incident X-band signal. Tuning devices in the X-band and K-band guides convert those guides into physically orthogonal resonant cavities tuned to the two frequencies. For maximum quality factor in the low power conversion formula $P_{out}=K\ P_{in}^2$, the geometry should be such that both the X-band and K-band cavity magnetic fields are maximized at the center of the ferrite. This formula becomes invalid, however, when P_{in} reaches values in the neighborhood of 1/K. As the saturation condition is approached a much more complicated consideration of losses is required. Uniform mode ferrite losses, RF losses to the cavity walls, losses due to conversion to higher harmonics, buildup of spinwaves, etc, need to be considered to accurately predict output conversion efficiency.

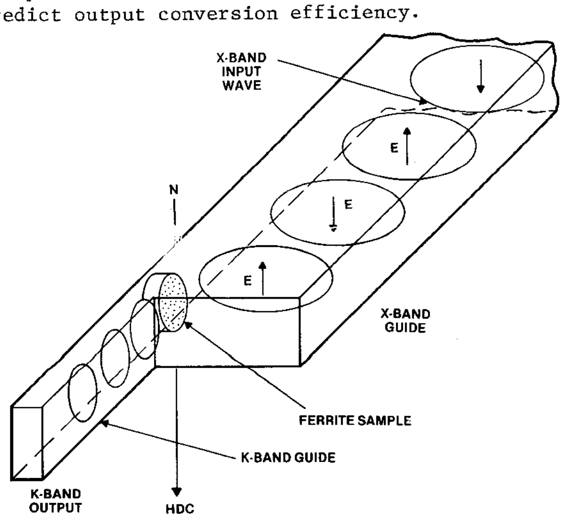

Figure 1. Waveguide Orientation for Harmonic Generator

Effects of short wavelength spinwaves are expected to be delayed by the spinwave buildup time, typically in the order of $(\Delta H_K)^{-1} \sim 0.1\ \mu$sec. The observed detected output wave shape under optimum tuning conditions was essentially identical with the input wave shape and showed no apparent spinwave buildup transients for input power levels of the order of 1/K. This incident power level of 1/K is about 10 dB above the theoretical spinwave threshold power level.[3] We can thus infer that a spinwave instability is not responsible for the harmonic power saturation phenomenon.

However, it was observed that resonant absorption occurred with buildup transient times below 0.1 μsec, often in the order of 50 nsec. These correspond to buildup times of low order Walker modes, whose ΔH_K values are expected to approach ΔH_o of the uniform precession.

It was also observed that resonant absorption occurred when using a highly uniform dc field. The peak output powers were higher, and density of resonant modes (at constant frequency, varying field, or vice versa) was less. This points to spurious low order Walker modes as the saturation mechanism for 2nd harmonic output.

Third harmonic oscillation was observed, but the power level when observed was about 27 dB below the fundamental.

To gain theoretical insight in the harmonic generation process under the condition $P_{in} \approx 1/K$, we developed the following exact equations for the behavior of the magnetization vector M in a spherical polar coordinate system (Figure 2). They are:

$$\theta = \frac{\omega_o \sin\theta}{1+\alpha 2} \left(-\alpha + \frac{h}{H_o \sin\theta}\left[-\sin\delta\phi + \alpha\cos\theta\ \cos\delta\phi\right]\right)$$

$$\phi = \frac{\omega_o}{1+\alpha^2} \left(-1 + \frac{h}{H_o \sin\theta}\left[\cos\theta\ \cos\delta\phi - \alpha\sin\delta\phi\right]\right)$$

where θ and ϕ are the polar angles describing the position of the magnetization vector, $\alpha = \frac{\Delta H}{H_o}$, h is the magnitude of the RF vector and $\delta\phi$ is the difference in azimuth angle ϕ between the magnetization vector and the RF field vector.

Inspection of these equations under conditions of dynamic equilibrium shows that dropping α^2 and replacing $\sin\theta$ with θ reduces these equations to those used in the first order analysis on which the square law power formula is based. Straightforward application of the above equations retaining terms in a α^2 leads to the power efficiency formula:

$$\frac{P_2}{P_{in}} = \frac{\gamma^2\ (1+\alpha^2)^2\ P_{in}}{2\pi\omega H_o^2\ \ (1+\frac{\alpha^2}{\cos\theta})^2\ \alpha eff}$$

where $\alpha = \frac{\Delta H}{Ho}$ must be replaced by a larger value, α_{eff}, which takes into account all circuit power losses,

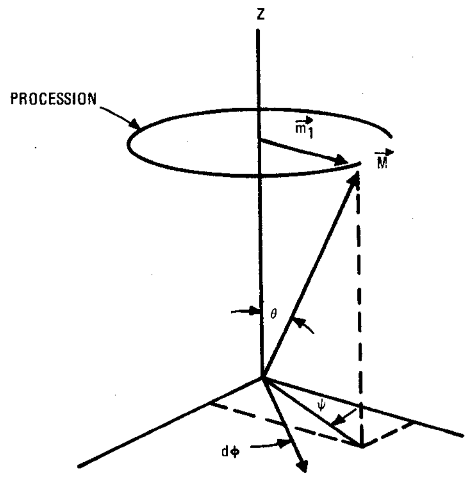

Figure 2. Magnetization $\overline{M}$ in a Spherical Coordinate System

including the power conversion. This rise in the effective damping constant of the uniform precession, when P_{in} becomes large, is the key to a realistic conversion efficiency formula, since holding α constant leads to predicted efficiencies greater than unity.

γ is the ratio of two counter rotating circularly polarized (C.P.) components of the nominally elliptically polarized input RF magnetic field; in the sense that the numerator of γ is in opposite rotation to the naturally precessing magnetization vector. This indicates the basic mechanism of the 2nd harmonic generation, shown in Figure 3. One C.P. component of the incident field tends to set the magnetization $\overline{M}$ into uniform precession, typical of most passive non-reciprocal ferrite devices. The other C.P. component converts uniform precession of $\overline{M}$ to 2nd harmonic motion in the direction Z of the applied dc field, by exerting a Z-directed force on $\overline{M}$ twice each cycle of the uniform precession.

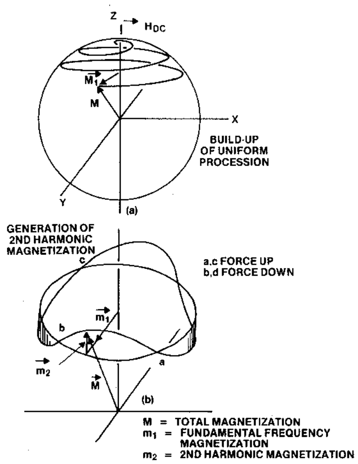

Figure 3. Mechanism of Second Harmonic Generation

The only references which we could find in the literature to conversion losses of less than 6 dB were in the paper by Wiener who obtained 35-40% efficiency over the input peak power range of 4 to 10 kW and an isolated statement claiming the achievement of 3 dB by Vartanian[3] whose published data[1] are consistently at or greater than 6 dB. We attained a 3.45 dB conversion loss, or 45% efficiency using a Calcium Vandium, Garnet with M_s of 1600 G at f=10.0 GHz, P_{in} =20 kW, 1 μsec pulsewidth, 0.06% duty, while getting 6.5 dB in the best case with polycrystalline garnet with M_s=1700, ΔH=45 Oe. The line width of only 12 Oe for the CVG 1600, compared to 45 Oe for the polycrystalline garnet is believed to be the main reason for this improvement in conversion efficiency. On the basis of simple uniform precession theory, the CVG 1600 should be nearly 6 dB better than the polysrystalline garnet, compared to the experimentally observed 3.05 dB. The general but not precise correlation of output power with $\frac{4\pi Ms}{H}$ is in agreement with the observations of Ayres[4] in doubling experiments at millimeter wavelengths. The large size of the ferrite samples used and their deviation from an ellipsoidal geometry make the well developed small sample theory only approximately applicable to our work. Our main resonance occurred at H_0=4530 Oe, compared to 3320 Oe, predicted by the Kittel formula.

$$\omega_r = (\gamma H_o + (Nx - Nz)\omega m)^{1/2}(\gamma H_o + (Ny - Nz)\omega m)^{1/2}$$

where $\omega m = 4\pi Ms$, while Nx, Ny, and Nz are the demagnetization factors for an ellipsoid of the equivalent diameter and length as the ferrite cylinder.

Additional resonances were found at fields of 4300, 4630, 4750, 5030, and 5170 Oe. Wiener[2] found a similar disparity between Kittel's theory and his observed main resonance. Since no precise theory exists for large ferrite samples it was not possible to determine whether the observed minor resonances were Walker modes or electromagnetic modes. However, since the mode density was highly dependent on the dc field uniformity, it is plausible to assume that they are Walker modes.

Although the details of coupling the uniform precession modes to Walker modes are unknown, it is plausible to assume that 2nd harmonic generation could provide the coupling because the harmonic field direction is normal to that of the uniform precession.

CONCLUSION

In conclusion, by the use of a low line width garnet, we have achieved conversion efficiency of 3.45 dB at 10 GHz and 12 W average (Figure 4) input power equal to that obtained by Wiener at 8.5 GHz and 3 W average input power. To the best of our knowledge, our average output power of 5.4 W at 20 GHz is the highest doubled output power achieved to date. It appears that output is limited by low order Walker modes. The conversion efficiency can be enhanced by adjusting the input magnetic field ellipticity.

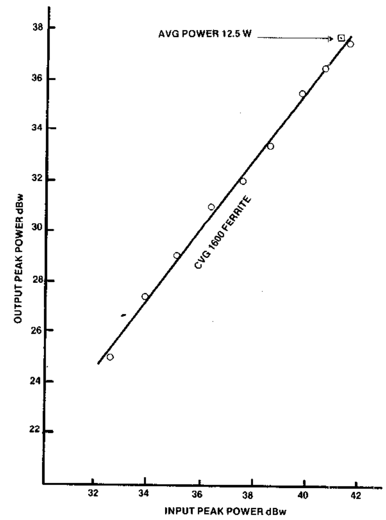

Figure 4.

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