Multi-Band Multi-Tone Tunable Millimeter-Wave Frequency Synthesizer For Satellite Beacon Transmitter

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Abstract — This paper presents the design and test results of a multi-band multi-tone tunable millimeter-wave frequency synthesizer, based on a solid-state frequency comb generator. The intended application of the synthesizer is in a satellite beacon transmitter for radio wave propagation studies at K-band (18 to 26.5 GHz), Q-band (37 to 42 GHz), and E-band (71 to 76 GHz). In addition, the architecture for a compact beacon transmitter, which includes the multi-tone synthesizer, polarizer, horn antenna, and power/control electronics, has been investigated for a notional space-to-ground radio wave propagation experiment payload on a small satellite. The above studies would enable the design of robust high throughput multi-Gbps data rate future space-to-ground satellite communication links.

Index Terms — Comb Generator, Propagation, Satellite, Synthesizer, Transmitter.

I. Introduction

The frequency spectrum allocated and utilized currently for satellite communications uplinks and downlinks are rapidly getting congested due to very heavy usage. The logical choice is to move higher up in frequency into the millimeter-wave (mm-wave) frequency bands, which are sparsely used. The mm-wave bands include frequencies in the Q-band (37 to 42 GHz) and the E-band (71 to 76 GHz). Migrating to the mm-wave frequency bands has the added advantages of smaller antenna size and lower mass for a given spacecraft effective isotropic radiated power (EIRP). In addition, the beamwidth for a given antenna size is smaller. The smaller beamwidth results in a smaller spot size, which allows packing a greater number of spot beams over a given area and thus enables greater spectral efficiency through frequency reuse. Prior to system planning and system design for deployment in space, it is essential to investigate the effects of Earth's atmosphere on radio wave propagation at the above frequencies. In general, radio waves suffer increasing attenuation, scintillation, depolarization, and group delay due to atmospheric gases, clouds and rain [1].

In this paper, we present the design, construction and test results for a multi-band multi-tone tunable mm-wave frequency synthesize based on the discrete frequency spectrum produced by a solid-state frequency comb generator (FCG). Unlike the single frequency beacon source, which flew on NASA's Advanced Communications Technology Satellite (ACTS) [2] for Ka-band propagation experiments [3], the multi-tone frequency synthesizer is capable of simultaneously delivering coherent multiple frequencies. These multiple frequencies enable wide band characterization of the frequency dependent group delay effects, which are essential for the design of robust high throughput multi-Gbps data rate future space-to-ground satellite communication links.

II. Tunable Multi-Tone Frequency Synthesizer Circuit Design, Construction and Mode of Operation

Harmonic generators are a convenient way to generate high frequency signals, when direct generation of the high frequencies is challenging. Harmonics are generated whenever a sinusoidal signal drives a non-linear capacitance. Such generators have become practicable because of the availability of high quality step-recovery diodes. The theory of harmonic generation using step-recovery diodes can be found in [4]. The multi-tone synthesizer consists of a FCG, which puts out evenly spaced harmonic frequencies of the input signal, which are coherent and tunable over a wide frequency range. These harmonics are then amplified to the power level needed for radio wave propagation studies. Harmonics that are amplified are simultaneously transmitted as beacon signals from space to receiving ground stations located at several climate zones within the CONUS. By measuring the signal relative strength and phase at ground sites one can estimate the attenuation and group delay or dispersion due to atmospheric induced effects.

III. Rational For Multi-Band Multi-Tones

Accurate models that predict the impairments to radio waves in the 20/30 GHz bands due to Earth's atmosphere are available. In addition, communications satellite systems are currently operational at these frequencies. It is also well understood that signals at Q-band and E-band frequencies would experience much higher attenuation during rain fades than signals in the 20/30 GHz range. The deep fades will result in poor signal-to-noise ratio (SNR) at the Q-band and E-band beacon receivers on ground, which could cause the receivers to lose frequency/phase lock. To overcome this problem it is desirable to include a coherent K-band (18 to 26.5 GHz) beacon source along with the Q-band and E-band beacon sources on the payload. Because of higher SNR at K-band, the beacon receiver on ground can retain lock during deep fades and thus enable high availability attenuation measurements or characterization. This data is valuable and can provide a reference for model development and also provide an understanding of frequency model scaling factors for future system design when Q-band and E-band propagation data is unavailable [1]. A block schematic and photograph of the K-band and Q-band multi-tone frequency synthesizer based beacon transmitter and breadboard coaxial test set up for characterization are presented in Figs. 1 and 2, respectively. The synthesizer consists of a wideband FCG. The K-band and Q-band harmonics are separated by bandpass (BP) filters and amplified to the power level required for radio wave propagation studies before transmission. Notice that the set up is very compact.

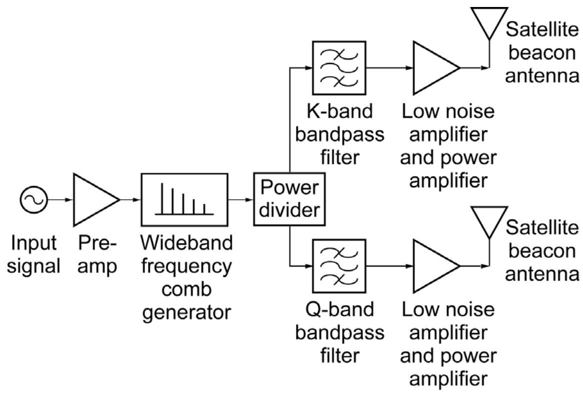

Fig. 1. Simplified block schematic of the K-band and Q-band multi-tone frequency synthesizer based beacon transmitter payload for radio wave propagation studies.

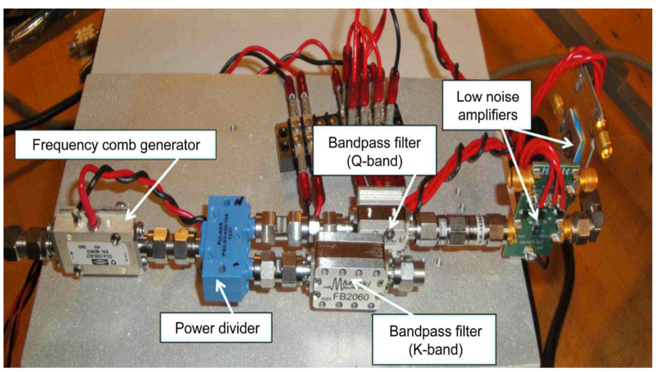

Fig. 2. K-band and Q-band coaxial test set up for characterizing the multi-tone frequency synthesizer.

The BP filters and the low noise amplifiers (LNAs) are appropriately selected for the two frequency bands. The measured K-band and Q-band spectrums are presented in Figs. 3 and 4, respectively. The tones are 1 GHz apart, but can be tuned by changing the frequency of the input signal to the FCG. Figures 5 and 6 present the results for the case when the tones are 500 MHz apart. These figures indicate that the spectrum is very distinct with excellent SNR. In addition, it is worthwhile to point out that the K-band and Q-band multi-tones are coherent since they are derived from a common input signal source as indicated in Fig. 1. A chain of MMIC based power amplifiers can further enhance the power levels such that the beacon EIRP is on the order of 30 dBW at the edge of CONUS coverage [5]. A minimum data collection period of 36 months is recommended and hence the above EIRP is the end of life value [1].

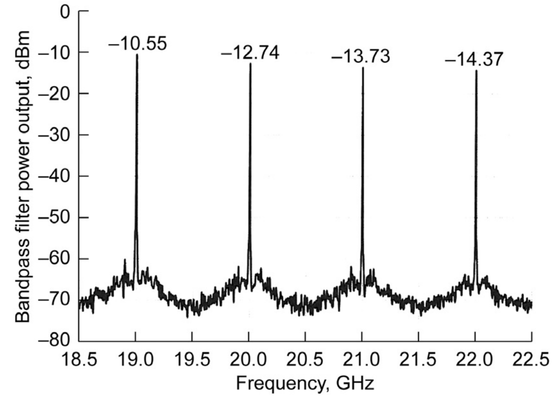

Fig. 3. K-band multi-tones at 1 GHz intervals as measured at the output of the BP filter. The power in each tone is indicated in dBm.

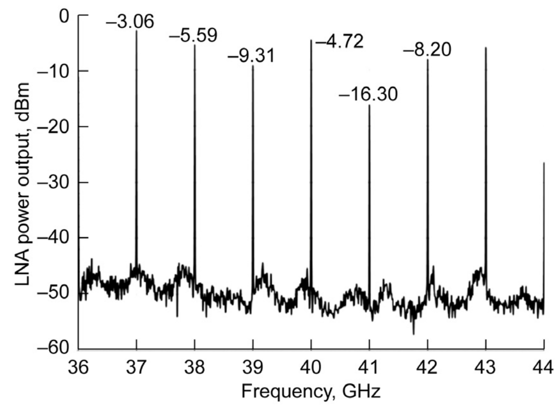

Fig. 4. Q-band multi-tones at 1 GHz intervals as measured at the output of the LNA. The power in each tone is indicated in dBm.

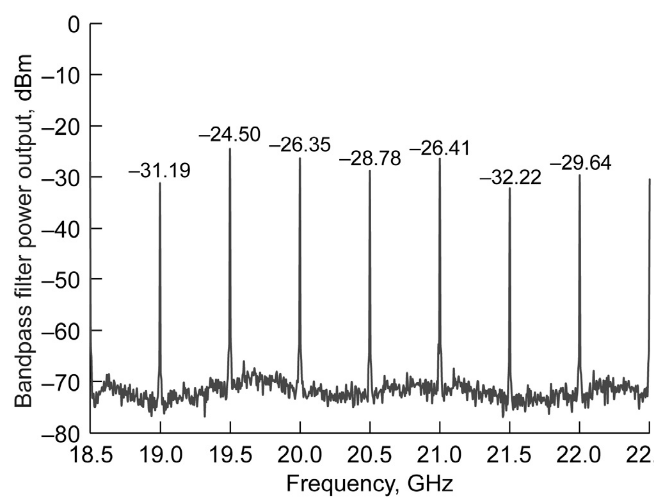

Fig. 5. K-band multi-tones at 500 MHz intervals as measured at the output of the BP filter. The power in each tone is indicated in dBm.

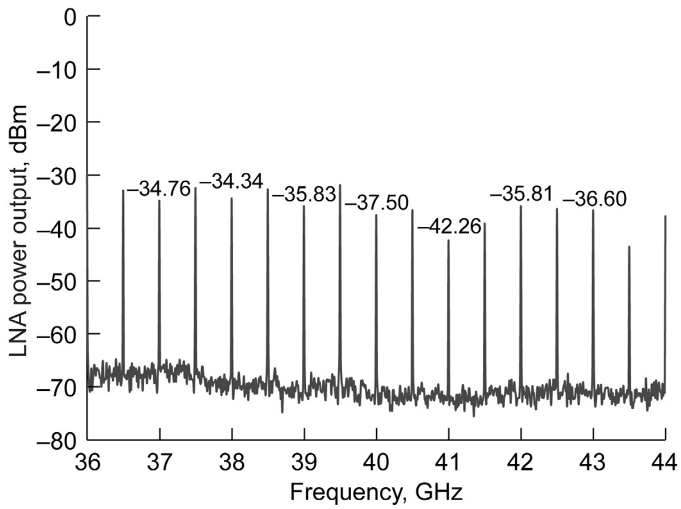

Fig. 6. Q-band multi-tones at 500 MHz intervals as measured at the output of the low noise amplifier. The output power level for each tone is indicated in dBm.

IV. E-Band Multi-Tone Frequency Synthesizer

A photograph of the E-band breadboard waveguide (WR-12) test set up is shown in Fig. 7. An E-band frequency extension module consisting of a harmonic mixer and a diplexer are used to extend the frequency range of the spectrum analyzer. The separation between the tones can be tuned by changing the frequency of the input signal to the FCG. The measured E-band spectrum at the output of the LNA is presented in Figs. 8 through 10. The plots are for tones that are 1, 2, and 3 GHz apart in frequency, respectively. The power in each tone is also indicated in the figures. Notice that the tones are very distinct with excellent SNR. In addition, spectrum analyzer measurements were conducted with the frequency span control set for narrow frequency range. As an example, Fig. 11 presents one such tone measured at the center frequency of 70 GHz with frequency span set equal to 100 MHz. The measurements indicate that the linewidth of the tone is on the order of 3 to 4 MHz close to the noise floor. A chain of MMIC power amplifiers can enhance the power of the tones to any desired level.

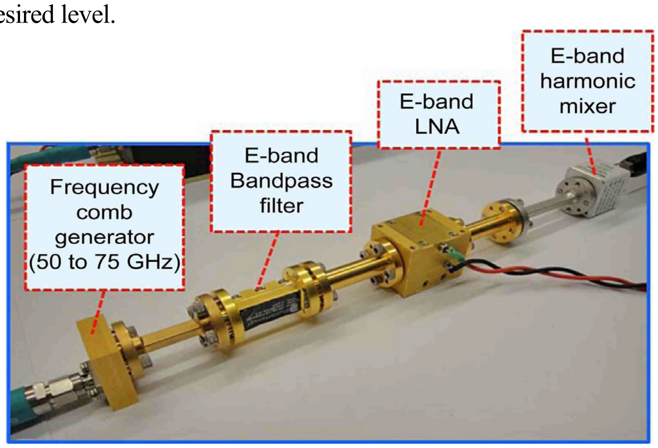

Fig. 7. E-band waveguide test set up for characterizing the multi-tone frequency synthesizer.

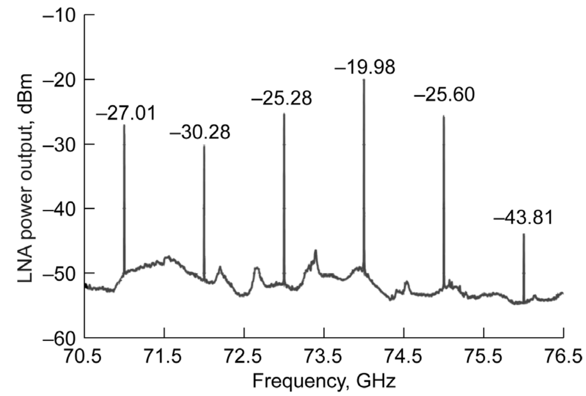

Fig. 8. E-band multi-tones at 1 GHz intervals as measured at the output of the LNA. The power in each tone is indicated in dBm.

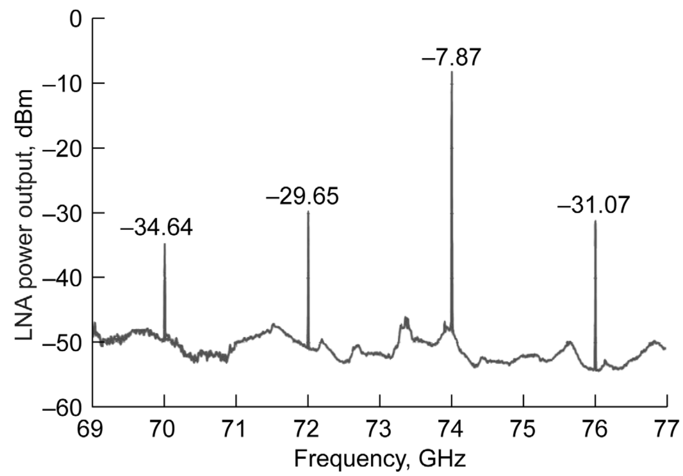

Fig. 9. E-band multi-tones at 2 GHz intervals as measured at the output of the LNA. The output power level for each tone is indicated in dBm.

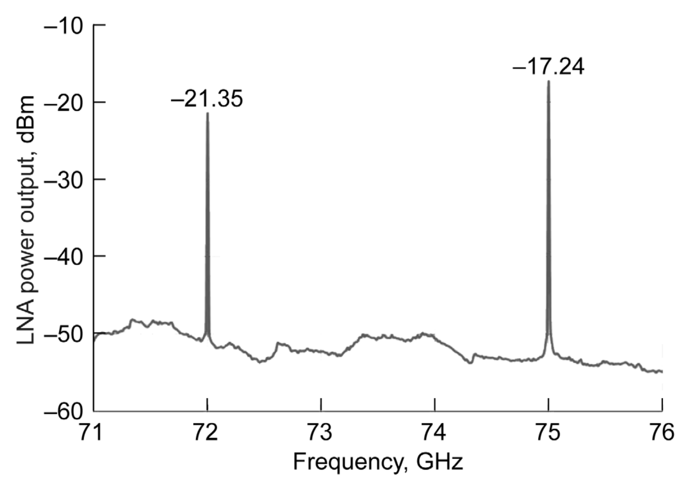

Fig. 10. E-band multi-tones at 3 GHz intervals as measured at the output of the LNA. The output power level for each tone is indicated in dBm.

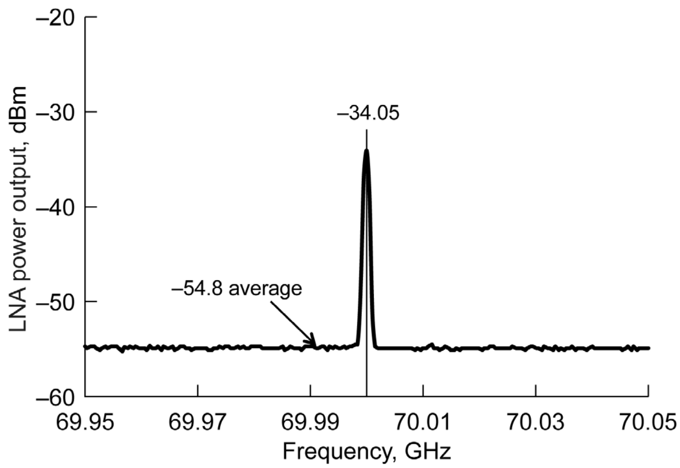

Fig. 11. Frequency spectrum of a single tone at E-band. The output power level for the tone and the noise floor are indicated in dBm.

V. Phase Noise Characteristics, Temperature Characteristics, and Space radiation Effects

The phase noise of the multi-tones degrades by 20 log of the multiplication factor. Hence, if the phase noise of the input signal source driving the FCG is –152 dBc/Hz at 10 kHz offset and if the multiplication factor is 20 then the phase noise of this tone is –152 + 20 log (20), which is –126 dBc/Hz. The measurements reported here were performed at room temperature. Hence, additional studies are required to quantify the effect of temperature on the multi-tone frequency synthesizer output frequency and power. Studies conducted by other researchers have indicated that the step recovery diodes are susceptible to neutron damage [6]. The degree of damage is dependent on the amount and time of exposure to neutron fluence. The intensity of the neutron fluence is dependent on the satellite's orbit.

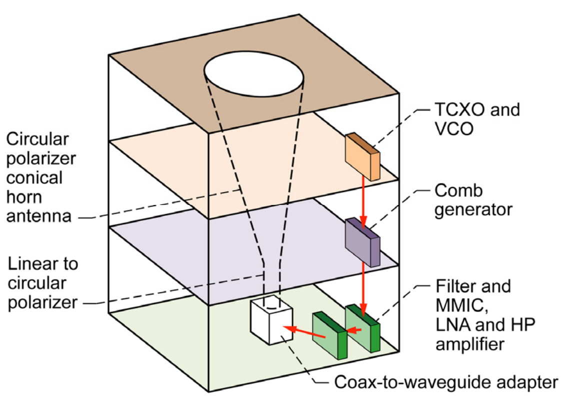

Fig. 12. Beacon transmitter chain accommodated inside a small satellite for a notional space-to-ground radio wave propagation experiment. For simplicity, prime power conditioning and other control circuitry has been omitted.

VI. Notional Small Satellite Space Experiment package

A basic multi-tone beacon transmitter chain, which includes the multi-tone synthesizer, polarizer, horn antenna, and power/control electronics, has been configured. The transmitter chain is compact enough to be accommodated inside a small satellite as illustrated in Fig. 12. The small satellite architecture is being investigated for a notional space-to-ground radio wave propagation experiment.

VII. Conclusions

The design, construction and test data for a K-band, Q-band, and E-band tunable multi-tone frequency synthesizer for radio wave propagation studies are presented. The tones are very distinct with excellent SNR. The beacon transmitter will enable wide band characterization of the frequency dependent group delay effects, which are essential for the design of robust high throughput multi-Gbps data rate future space-to-ground satellite communication links. Finally, a simplified layout for a compact multi-tone beacon transmitter for a notional space-to-ground radio wave propagation experiment payload on a small satellite has been presented. Besides, radio wave propagation studies, the multi-tone frequency synthesizer can be used for space borne active remote sensors like scatterometers, which require coherent, highly stable multi frequency signals.

Acknowledgments

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