28.4 A High-Q Resonant Inductive Link Transmit Modulator/Driver for Enhanced Power and FSK/PSK Data Transfer Using Adaptive-Predictive Phase-Continuous Switching Fractional-Capacitance Tuning

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As well as transferring power, inductively coupled systems such as RFID and wireless charging commonly require a downlink channel to transfer data to the receiving function, for simplicity usually using the same carrier frequency used for the power transfer. A high-Q factor resonant transmitter coil is highly desirable to create the strong magnetic field required for a practical operating range. However, this not only raises major problems with sensitivity to tolerances and environmental factors, but also seriously restricts the available bandwidth and hence downlink data rate. Amplitude Shift or On-Off Keying (ASK/OOK) are commonly used to allow simple demodulation, but in addition to the Q factor restricting the data rate, the average power transfer will be reduced by around 50%. Frequency Shift Keying (FSK) or Phase Shift Keying (PSK) are attractive inasmuch as the nominally constant envelope provides a potentially higher power throughput, but the data rate issue with a high-Q transmitter still remains. This is obvious for FSK, where by definition operation cannot be maintained away from the transmitter antenna's resonance frequency. Less obviously, for PSK applied to a nominally constant frequency carrier, the stored energy in the transmit tuned circuit will slow the phase transitions making demodulation more difficult; for binary PSK the amplitude will also drop significantly at each symbol transition. Note that the receiver Q factor is usually lower to avoid the need for active tuning in a micropower circuit.

Thus in order to derive benefits from FSK or PSK it is essential to solve the problem of maintaining resonance during frequency or phase deviations. In prior art [1] an array of selectable capacitors has been employed to achieve resonance, with the elements also switched synchronously with the modulation, but the detection of resonance in real time is still a bottleneck, and does not solve the problem for PSK modulation. Furthermore, a large number of capacitors, HV switches and control lines are required for precise tuning to resonance at high-Q to compensate for detuning effects and component tolerances. Adaptive real-time tuning of a driven resonant circuit can be achieved by synchronously switching a capacitor in and out of circuit within each cycle, where the duty cycle determines the average capacitance [2]. Resonance is maintained with external magnetic loading and across PVT variations by sensing the voltage across the switch each cycle at the closure instant, and determining the direction of error from resonance to close a control loop (fig. 1) similar to a conventional PWM system. In an analogue implementation, the excitation source also generates a triangle signal that is compared with tuning voltages $V_{TN+/-}$ to determine the switch timing.

With a single tuning feedback loop, smooth variations in the excitation frequency can be tracked at the cost of a small residual error increasing with deviation rate, but abrupt frequency transitions still result in a finite settling time. However, if the excitation is always switched between two defined FSK symbol frequencies, it is possible to use two separate tuning feedback loops, and select which one has control using the modulation data input. At either of the FSK symbol frequencies the active tuning loop can be updated with error information to compensate for parametric drift, while the inactive loop is held in its last active state pending the next frequency transition. Thus resonance is maintained at all times. To preserve the continuity in the current circulating in the transmit resonant circuit, it is important that the excitation phase is continuous and the changeover between the tuning loops is synchronised precisely with the zero crossing of the antenna voltage waveform V_C. Sensing this condition would be cumbersome, but we can easily infer the correct timing from the phase of the excitation drive, on the basis that at resonance it will be known precisely. Figure 2 shows the concept using similar hardware to figure 1. At the instant that the frequency is switched from F_L to F_H the tuning control voltages $V_{TR+/-}$ can be seen to jump to new stored values, setting the capacitor switch timing to the previous settled values at resonance. This concept may be extended with more than two control loops to allow multiple defined discrete frequencies to be used.

This continuously resonant FSK arrangement can be adapted to handle PSK [3]. A positive or negative phase rotation may be implemented by a temporary increase or decrease in the excitation frequency. A precise phase rotation can thus be achieved by using a defined offset frequency for a defined number of cycles, and hence an adaptive tuning system with at least three control loops can maintain continuous resonance. Two frequencies F_H and F_L need to be set so that they create the required net phase angle θ_{LEAD} or θ_{LAG} relative to the nominal frequency F_C over the allocated number of cycles N for the phase shift. Equations 1 and 2 give the required F_L for phase lag and F_H for phase lead respectively, in terms of F_C, θ in radians and N.

$$F_L = \frac{2\pi \cdot F_C}{2\pi + \frac{\theta}{N}} \quad (1) \qquad F_H = \frac{2\pi \cdot F_C}{2\pi - \frac{\theta}{N}} \quad (2)$$

In practice, the wide frequency shifts possible with 3 adaptive tuning loops mean QPSK modulation can be achieved with as few as 2 cycles at each offset frequency. In order for resonance control to function and phase to be continuous it is important to control not only the timing of the frequency transitions but also the precise value of the offset frequencies. Implementation of the system in a fast process using digital synthesis would allow precise setting of both frequency and exact phase transition timing. However in the "smart power" process used, manual setting is employed for F_H and F_L, although adaptive frequency trimming to compensate for PVT variation is also quite practical.

Figure 3 shows the architecture for a combined driver, tuner and modulator integrated using a mixed-signal architecture in a 0.18µ 1.8V/5V/50V CMOS/LDMOS process, operating over 10kHz – 2MHz and intended to drive up to 100mA in a resonant transmit coil, with a die area of 4.8mm^2 (limits set by project time/budget constraints). The fixed and fractional capacitors C_1 and C_2 (fig. 1) are realised as equal capacitors C_N and C_P, alternately switched by separate P and N HV devices on the positive and negative excursions of V_C, avoiding the need for an ideal bi-directional switch. This gives a min:max tuning range of 1:1.41, sufficient to permit both compensation of tolerance/environmental effects as well as the required frequency shifting for FSK/PSK data modulation. Capacitive dividers isolate the high voltages on the tuning capacitors from the tuning control input [2]. The timing reference is derived from a current integrator oscillator, creating V_{TR} and V_{DR}, the currents generated by a digital V-to-I function. In PSK mode, a FSM manages transitions between the PSK frequencies to create phase lead/lag as appropriate. The FSM is synchronous with the mid-point crossings of V_{TR}, denoted by V_{TRLIM}, providing ideally synchronous selection of operating frequency and active tuning loops at resonance.

Figure 4 compares FSK operation with a fixed-tuned inductor and the adaptive-predictive system, using a 30µH inductor at 2MHz with a Q of 50. At the FSK *mark* frequency the fixed-tuned antenna circuit is no longer resonating and hence there is a significant reduction in the circulating current. By contrast, the adaptive-predictive system synchronously changes both the drive and antenna resonant frequencies such that there is a negligible reduction in V_C, hence the magnetic field strength around the inductor is maintained. QPSK operation of the adaptive-predictive system is shown in figure 5 with phase lead and lag at 2MHz on the same antenna circuit. In both cases the transition occurs over 4 cycles due to an appropriate frequency shift (approx. ±6.5% adjustment of nominal frequency), maintaining a large amplitude of oscillation during this time. Figure 6 shows a comparison between the achievable data rates of the adaptive-predictive system and OOK/FSK/PSK based on simulations of a fixed-tuned antenna circuit. With a Q of 50 the presented architecture provides an improvement of over 8x (PSK) and 30x (FSK) in the data rate and induced EMF improvement of up to 4.5x at maximum data rate compared with a fixed-tuned antenna. Measured FSK and QPSK modulation waveforms are shown at the maximum data rates.

[1] R. Hash and D. Bowman, "Data communication system harnessing frequency shift keyed magnetic field", US Patent US6349116B1, Feb 2002

[2] H. Kennedy et al., "A Self-Tuning Resonant Inductive Link Transmit Driver Using Quadrature-Symmetric Phase-Switched Fractional Capacitance", *ISSCC*, Feb. 2017

[3] W Redman-White, "Electronic Tuning System", UK Patent GB2539113B, October 2017

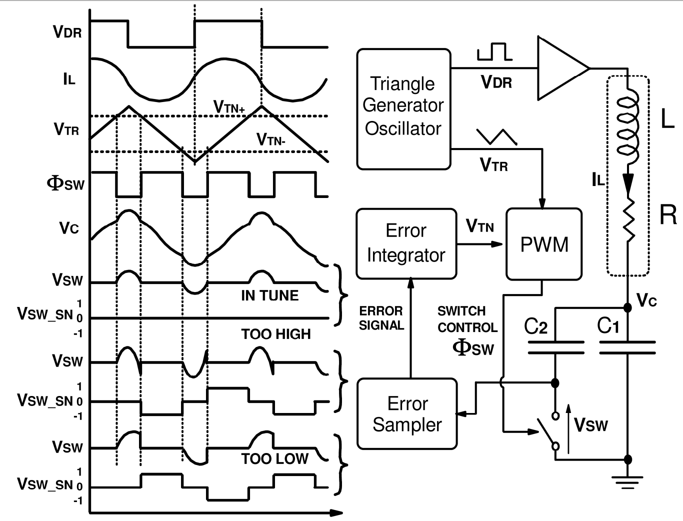

Figure 28.4.1: Left: Timings for adaptive tuning LC circuit using quadrature phase-switched fractional capacitance. Right: tuning system block diagram

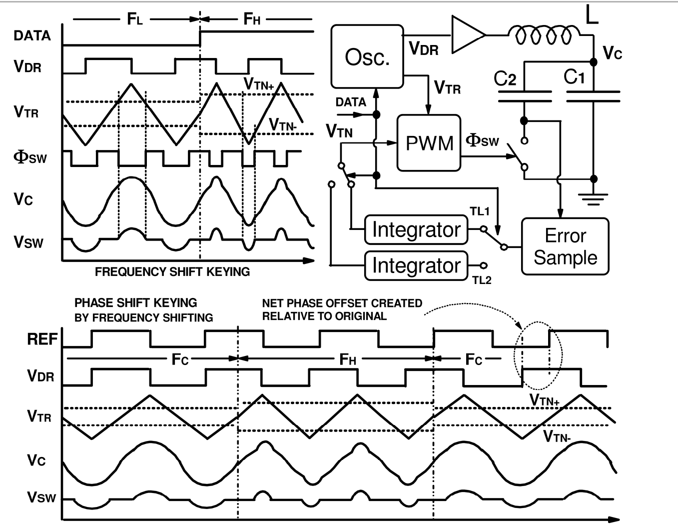

Figure 28.4.2: Top left: FSK with instantaneous frequency and tuning step. Top right: system architecture for adaptive-predictive tuning during FSK. Bottom: PSK phase advance by short-duration frequency offset

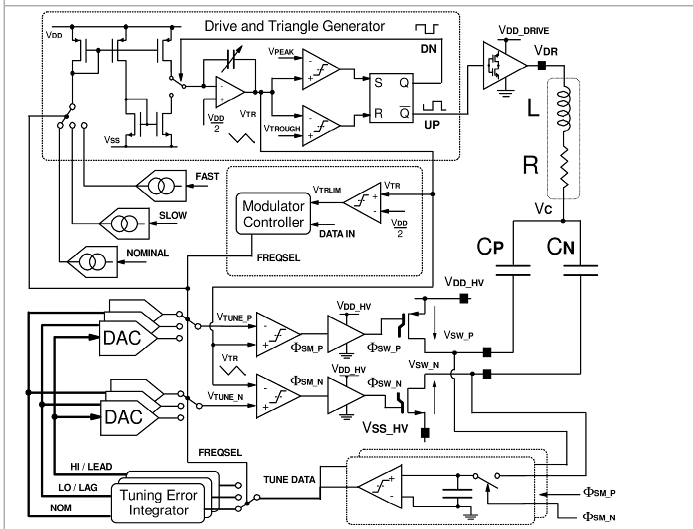

Figure 28.4.3: Circuit architecture of adaptive-predictive self-tuning system for antenna driver/modulator

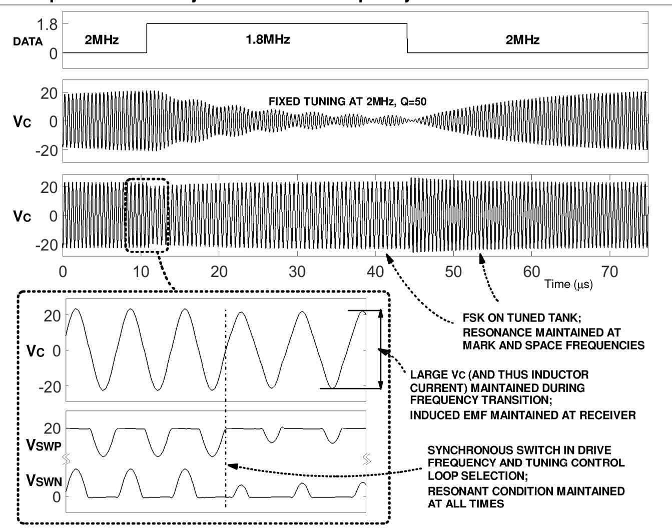

Figure 28.4.4: Wideband FSK measurement, F0=2MHz, F1=1.8MHz, Q = 50. Fixed-tuning circuit, (top, upper), adaptive-predictive tuning, (top, lower)

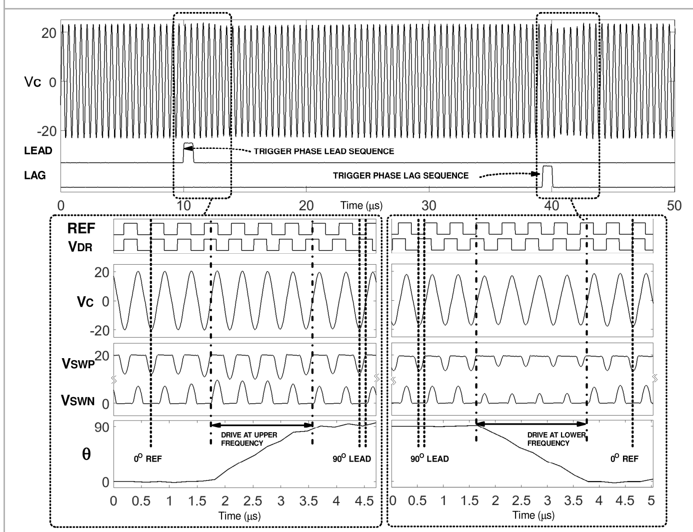

Figure 28.4.5: QPSK modulation measurement, FC= 2MHz, FH = 2.13MHz, FL = 1.88MHz, antenna circuit Q = 50. Phase lead (left) and phase lag (right)

For Q = 50 2MHz carrier frequency	This work		Fixed-tuning Inductor		
	FSK[1]	O-QPSK	OOK	FSK[2]	O-QPSK
Symbol transition time (µs) to within 1% of settled value	0.5	0.875	37.5	66.0	27.5
Maximum data rate (kbps)	500	296	26.6	15.1	36.4
Normalised induced EMF at maximum data rate	1	1	0.607	0.216	0.862

1 : F0 = 1.8MHz, F1 = 2MHz, adaptive-predictive tuning
2 : F0 = 1.8MHz, F1 = 2MHz, fixed tuning at 1.9MHz mean frequency

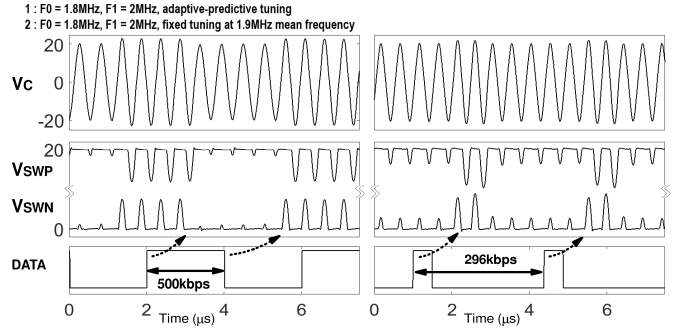

Figure 28.4.6: Top: Achievable data rate and power delivery for adaptive-predictive tuning vs fixed-tuning. Bottom left: Measured FSK modulation (max data rate). Bottom right: Measured PSK modulation (max data rate)

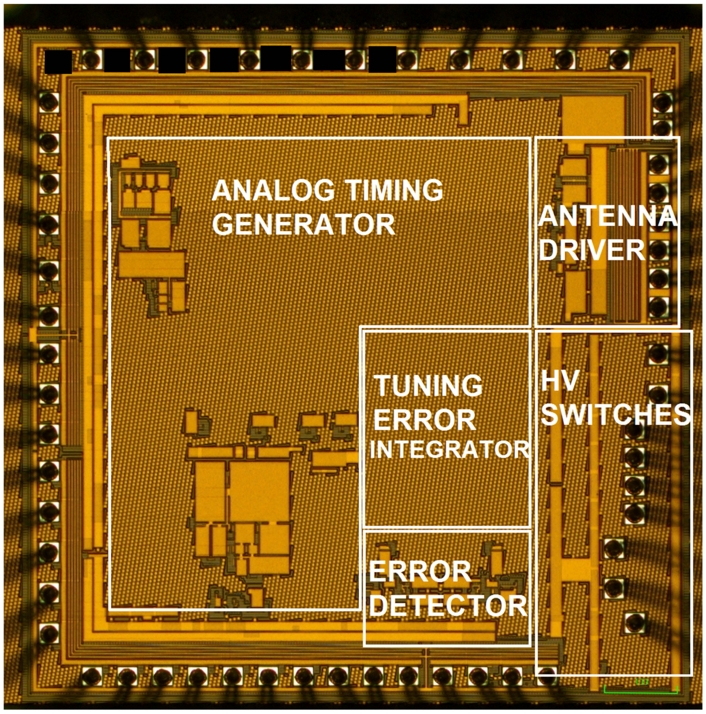

Figure 28.4.7: Die micrograph