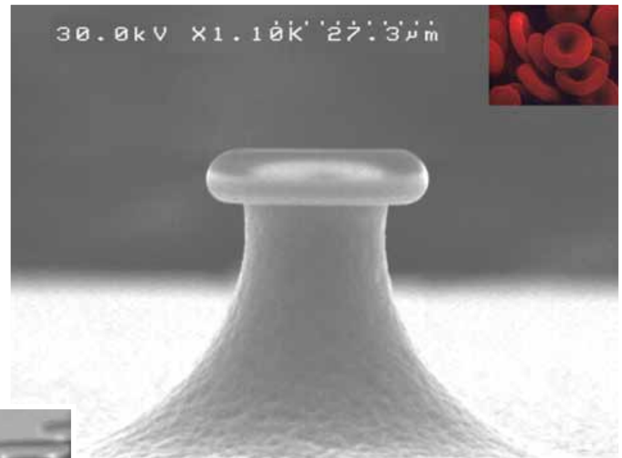
High-Q for Photons

Nonlinear Resonators for Light

by Kerry J. Vahala

Since the mid 90s, information traveling as a lightwave on optical fiber has been multiplexed spectrally. One can imagine this process as information streams or channels traveling at distinct colors, with each color providing a channel of information—much like in television or radio transmission. Some time ago, the requirement to combine and separate these channels triggered interest in compact optical resonators[1]. Like their counterparts in electronics, these devices could be used to select or combine channels by the process of filtering signals according to frequency. Resonators, whether electronic, optical, or even acoustic, have in common the idea of energy storage at a particular frequency. The pitch of a tuning fork is a good example in the acoustic realm; and the purity of the pitch is a mathematical property that can be related to how long energy is stored. This storage time is conveniently given in terms of the number of cycles of vibration of the signal, and is called the "Q factor." A tuning-fork resonator, for example, will have a Q factor in the range of 10,000. Another important resonator, the quartz crystal used in electronics, can have Q factors as high as 1 million. Such a high purity-of-pitch makes quartz resonators useful in many applications, such as the familiar quartz wristwatch.



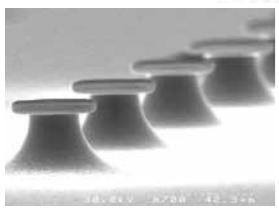


Figure 1: An array of silica microtoroids (lower left) and a close-up side-view of an individual device (main panel). Light orbits the perimeter of the donut-shaped toroidal structure and is confined for a relatively long time because of the smooth glass surface. For a size comparison, red blood cells are shown in the upper right panel.

In optical communications, the Q factor of the best semiconductor, chip-based resonators hovered around 10,000 until about 7 years ago. At that time, a technique for fabrication of optical resonators called microtoroids was developed my research group[2]. The toroid is fabricated of silica glass on silicon wafers that are similar to those used in electronics; and they hold light within a tiny ring-shaped orbit (see Figure 1). Normally, photons, the unit particle of light, are knocked from such orbits by imperfections in the glass such as the surface roughness created by the semiconductor processing, itself. However, through a special processing technique, the surface of these microtoroid resonators is smoothed to the atomic scale. The photons, in turn, enjoy a very smooth ride and remain in orbit a long time (high Q). Microtoroid resonators hold a record, even today, for on-chip devices. They feature Q factors in excess of 100 million. Moreover, because their fabrication relies upon many tools developed by the semiconductor processing industry, these Q values are obtained with a high yield so that many devices can be fabricated on a single chip.

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This leap in optical Q factor was so large that entirely new devices have become accessible using microtoroid resonators on silicon chips. Narrow-band filters ("high purity pitch") with footprints smaller than the width-of-a-hair provide one example. However, we have also found that when energy storage can be boosted and concentrated into small volumes other effects can also occur. To understand some of these, imagine the photons of light as cars and their orbits within the microtoroid as a roundabout for the cars. The storage time (Q factor) of the microtoroid would determine how many times the cars must circle before leaving the roundabout. Clearly, as storage time increases, even a trickle of input traffic creates congestion. Such traffic congestion is made far worse in the microtoroid, by its small size. In fact, a trickle of input photons (meaning very-low input power) is sufficient to create such intense congestion that photon collisions become very likely. Unlike the collisions of automobiles, photon collisions can be precisely engineered to have useful outcomes (through control of the shape and size of the microtoroid). For example, in a process called third-order upconversion, three photons at a given wavelength can fuse together upon collision into a single, much higher energy photon. Using this process, microtoroids can generate visible light that is color tunable (see Figure 2) beginning with input infrared photons provided by compact laser sources made for the telecom industry[3].

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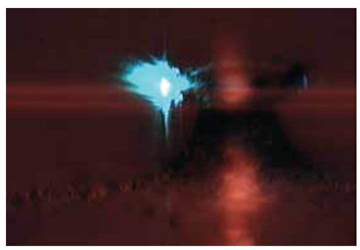

Figure 2: A nonlinear optical process called third-order upconversion is caused by the collision of three photons and the subsequent emergence of a single, higher-energy photon. In the upper panel, a single infrared beam of light is coupled into a microtoroid (out of focus in the panel) and blue (higher energy photons) are created. In the lower panel, two different wavelengths of infrared light are coupled in opposite directions into a single microtoroid (cross-section is sketched as dashed lines) and these produce two distinct, visible colors upon upconversion. The optical power level required for this process to occur is very low on account of the high storage time (high Q factor) of the microtoroid device.

In yet another kind of interaction, two photons can bump into one another; and exchange energy. In this fender-bender-like collision the photons emerge with new colors (one shifted to the red and other to the blue end of the spectrum): a fundamental process that enables a very useful device called a parametric oscillator. Through a combination of their high-Q, small volume, and shape-engineered properties, microtoroids achieved the first demonstration of these devices in any microcavity[4].

Like the force a driver experiences when making a sharp turn, photons also apply a force on the glass interface of the microtoroid. Individual photons provide a negligible force, but here again because of the high density of photons, their collective force is sufficient to inflate the microtoroid by a small amount (a few picometers). Like a guitar string whose length is changed while being struck, this change in the toroid size also shifts the pitch (color) of the circulating light. Because the pitch depends on how many photons are circulating inside the microtoroid, two strange effects are possible. In a first, the photon pressure transfers energy to the mechanical structure and causes it to vibrate from radio to the microwave frequencies. As such, this first effect produces what is called regenerative or self-sustained oscillation, a very useful phenomenon at the heart of all communication systems. The fact that this oscillation is both optically powered, and the output signal is itself also a lightwave (albeit modulated with the oscillations) endows the device with insensitivity to normal electromagnetic interference effects[5].

The second effect emerges by slightly adjusting the wavelength of the applied photons. When this is done, the flow of energy can be reversed so that power flows from the mechanical structure of the microtoroid to the photons. This transfer of energy cools the mechanical motion and is now the subject of an intense, world-wide effort to achieve what is called the quantum ground-state of motion for an oscillator.

Looking to the future, one of the frontiers of communications is the question of how to best utilize the quantum properties of light for information transmission. In this context, the subject of cavity quantum electrodynamics provides a tool for reversible transfer of information stored on a photon into matter (atoms). A prerequisite for this transference is that optical losses must be greatly reduced so that the underlying quantum principles are dominant. In this regard, the microtoroid resonator provides a new approach to these studies. In collaboration with Professor Jeff Kimble in the Caltech Physics department, the Vahala group has helped demonstrate the first single-atom cavity QED measurement on a chip. This work offers a pathway to higher levels of functionality within the subject of quantum information studies. Besides these studies there are efforts underway to increase the functionality of ultra-high-Q devices including integrated waveguides as opposed to the optical fiber device now in use. Such an addition would greatly extend the range of applications of these remarkable devices.

Continuing Impact of Lee Center

Finally, if photons can travel in closed, circular paths for long periods of time (and hence effectively over a great distance) can they also be made to travel along open-ended, paths over the same distance on a semiconductor chip? The question is important as several applications would benefit. These range from bio sensors to high-performance synthetics filters and phased-array radars. The microtoroid result has challenged conventional thinking on optical loss for photonic waveguides; and created interest in "fiber-like-losses" for microphotonic circuits. These ideas are now being developed further at Caltech and elsewhere under support from DARPA.

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Read more at: http://www.vahala.caltech.edu

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