Getting amped: Researchers develop instrument for exploring the cosmos and the quantum world

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The new amplifier consists of a superconducting material (niobium titanium nitride) coiled into a double spiral 16 millimeters in diameter. Credit: Peter Day

Researchers at the California Institute of Technology (Caltech) and NASA's Jet Propulsion Laboratory (JPL) have developed a new type of amplifier for boosting electrical signals. The device can be used for everything from studying stars, galaxies, and black holes to exploring the quantum world and developing quantum computers.

"This amplifier will redefine what it is possible to measure," says Jonas

Zmuidzinas, Caltech's Merle Kingsley Professor of Physics, the chief technologist at JPL, and a member of the research team.

An amplifier is a device that increases the strength of a weak signal. "Amplifiers play a basic role in a wide range of scientific measurements and in electronics in general," says Peter Day, a visiting associate in physics at Caltech and a principal scientist at JPL. "For many tasks, current amplifiers are good enough. But for the most demanding applications, the shortcomings of the available technologies limit us."

Conventional transistor amplifiers—like the ones that power your car speakers—work for a large span of frequencies. They can also boost signals ranging from the faint to the strong, and this so-called dynamic range enables your speakers to play both the quiet and loud parts of a song. But when an extremely sensitive amplifier is needed—for example, to boost the faint, high-frequency radio waves from distant galaxies—transistor amplifiers tend to introduce too much noise, resulting in a signal that is more powerful but less clear.

One type of highly sensitive amplifier is a parametric amplifier, which boosts a weak input signal by using a strong signal called the pump signal. As both signals travel through the instrument, the pump signal injects energy into the weak signal, therefore amplifying it.

About 50 years ago, Amnon Yariv, Caltech's Martin and Eileen Summerfield Professor of Applied Physics and Electrical Engineering, showed that this type of amplifier produces as little noise as possible: the only noise it must produce is the unavoidable noise caused by the jiggling of atoms and waves according to the laws of quantum mechanics. The problem with many parametric amplifiers and sensitive devices like it, however, is that they can only amplify a narrow frequency range and often have a poor dynamic range.

But the Caltech and JPL researchers say their new amplifier, which is a type of parametric amplifier, combines only the best features of other amplifiers. It operates over a frequency range more than ten times wider than other comparably sensitive amplifiers, can amplify strong signals without distortion, and introduces nearly the lowest amount of unavoidable noise. In principle, the researchers say, design improvements should be able to reduce that noise to the absolute minimum. Versions of the amplifier can be designed to work at frequencies ranging from a few gigahertz to a terahertz (1,000 GHz). For comparison, a gigahertz is about 10 times greater than commercial FM radio signals in the U.S., which range from about 88 to 108 megahertz (1 GHz is 1,000 MHz).

"Our new amplifier has it all," Zmuidzinas says. "You get to have your cake and eat it too."

The team recently described the new instrument in the journal *Nature Physics*.

One of the key features of the new parametric amplifier is that it incorporates superconductors—materials that allow an electric current to flow with zero resistance when lowered to certain temperatures. For their amplifier, the researchers are using titanium nitride (TiN) and niobium titanium nitride (NbTiN), which have just the right properties to allow the pump signal to amplify the weak signal.

Although the amplifier has a host of potential applications, the reason the researchers built the device was to help them study the universe. The team built the instrument to boost microwave signals, but the new design can be used to build amplifiers that help astronomers observe in a wide range of wavelengths, from radio waves to X rays.

For instance, the team says, the instrument can directly amplify radio signals from faint sources like distant galaxies, black holes, or other exotic cosmic objects. Boosting signals in millimeter to submillimeter wavelengths (between radio and infrared) will allow astronomers to study the cosmic microwave background—the afterglow of the big bang—and to peer behind the dusty clouds of galaxies to study the births of stars, or probe primeval galaxies. The team has already begun working to produce such devices for Caltech's Owens Valley Radio Observatory (OVRO) near Bishop, California, about 250 miles north of Los Angeles.

These amplifiers, Zmuidzinas says, could be incorporated into telescope arrays like the Combined Array for Research in Millimeter-wave Astronomy at OVRO, of which Caltech is a consortium member, and the Atacama Large Millimeter/submillimeter Array in Chile.

Instead of directly amplifying an astronomical signal, the instrument can be used to boost the electronic signal from a light detector in an optical, ultraviolet, or even X-ray telescope, making it easier for astronomers to tease out faint objects.

Because the instrument is so sensitive and introduces minimal noise, it can also be used to explore the quantum world. For example, Keith Schwab, a professor of applied physics at Caltech, is planning to use the amplifier to measure the behavior of tiny mechanical devices that operate at the boundary between classical physics and the strange world of quantum mechanics. The amplifier could also be used in the development quantum computers—which are still beyond our technological reach but should be able to solve some of science's hardest problems much more quickly than any regular computer.

"It's hard to predict what all of the applications are going to end up being, but a nearly perfect amplifier is a pretty handy thing to have in your bag of tricks," Zmuidzinas says. And by creating their new device, the researchers have shown that it is indeed possible to build an essentially perfect amplifier. "Our instrument still has a few rough edges that need polishing before we would call it perfect, but we think our results so far show that we can get there."

More information: The title of the *Nature Physics* paper is "A wideband, low-noise superconducting amplifier with high dynamic range."

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